Annual Research Report
ARR-2-15-98

This report was prepared for the
U.S. Department of Transportation
National Highway Traffic Safety Administration
Office of Crash Avoidance Research
by the University of Michigan Transportation Research Institute (UMTRI)

Fostering Development, Evaluation, and Deployment of Forward Crash Avoidance Systems (FOCAS)

Cooperative Agreement No. DTNH22-94-Y-47016

UMTRI Report No. 98-32

Reporting Period: January 1997 to February 1998

Zevi Bareket
Paul S. Fancher
Robert D. Ervin

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UMTRI The University of Michigan Transportation Research Institute

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16. Abstract

This work is part of a multiyear program to foster the development, evaluation, and deployment of forward crash avoidance systems. The work performed during the first two years of this program addressed adaptive cruise control and warnings based upon the motion and proximity of preceding vehicles in the path of travel. The research work done in the first and second years has provided a foundation for the work performed in this third year . The technology-related work for the third year was focused upon the addition of braking to an UMTRI prototype of an ACC system. The objective of this work is to provide test results and system-development experience showing the engineering and human factors issues posed by braking as a supplement to ACC or within a medium-deceleration crash avoidance function. The results indicated that the acceleration level used in increasing the speed of the ACC vehicle was not satisfactory in the opinion of most of the test drivers. Drivers did not want to slow down too much because they were concerned with how long it would take to get back up to the desired speed and headway time gap. They indicated that the resume rate of the system was the system's weakness. With regard to the buzzer that was used to warn the driver when the system was asking for the maximum deceleration authority, there were some drivers who did not like buzzers in general and some drivers who thought the features of this buzzer could be improved. The ratings concerning the deceleration level, the following control, and the system's smoothness were quite good. It is recommended that a simple rule for modulating the throttle should be used to achieve the basic ACC functionality. Braking should be applied in a progressively increasing manner, and it should be used to adjust vehicle deceleration in a way that will lead to headway time and distance gaps such that throttle modulation can control headway. Every effort should be made to improve the forward-acceleration capability of the vehicle when it is under ACC control. The warning system should have a nonaggressive signal to inform the driver when braking at the full-deceleration authority of the ACC system has been reached. Further consideration should be given to adding another, more aggressive, signal to warn the driver when the deceleration needed to barely avoid a crash exceeds the control authority of the ACC system.

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Executive Summary

The overall goal of this multiyear program is to foster the development of a range of commercialize-able sensors and associated application systems that supplement the forward crash-avoidance performance of drivers. To aid in achieving this goal, the program seeks not only to build prototype systems but also to create evaluation tools, methodologies, and knowledge as needed to expedite the development of adaptive cruise control (ACC) and forward crash avoidance (FCA) systems including forward collision warning (FCW) systems.

A key feature of the program for this year has been the addition of a new partner, ITT Automotive, Inc. This addition along with ADC, GmbH (which is an original partner) allowed UMTRI to integrate its control algorithms into a working ACC-with-braking system. Specifically, ITT furnished a vehicle equipped with a prototype of their smart booster system, thereby providing the mechanism for electronically controlling the brakes. To allow communication with the smart booster, ADC reconfigured the vehicle application controller (VAC) that is built into the ACC package.

The work performed during the first two years of this program addressed adaptive cruise control operation and warnings based upon the motion and proximity of preceding vehicles in the travelling path. This work provided a foundation for the research performed in this third year, which focused on the implementation of braking in UMTRI's prototype of an ACC system. The objective of this work is to provide test results and system-development experience showing the engineering and human-factors issues raised by braking as a supplement to ACC, or as a limited crash-avoidance function.

This annual report, which is the third year's deliverable, presents detailed information with respect to:

- The prototype ACC-with-braking system that was developed during this year
- The vehicle platform in which the ACC-with-braking system is installed
- Test results and experience gained by driving the vehicle equipped with the system
- Findings derived from the results
- Plans and expectations for next year

The findings of this year's work show that ACC systems with a moderately high deceleration authority (0.22 g), can provide a level of headway control that would be both useful and well-liked by many drivers. The results are not extensive enough to provide

definitive information with respect to safety consequences and the acceptance of warning sounds. Subjective ratings from 15 test drivers with previous ACC experience indicate that the prototype system performed its basic ACC functionality comfortably and conveniently, however certain features of the system need to be improved.

Ratings by the drivers concerning the deceleration level, the following control, and the system's smoothness were quite good. Based upon this experience it is recommended that basic ACC functionality should be achieved by a simple throttle-modulating rule. When headway control cannot be done effectively by throttle modulation only, braking should be applied in a progressively-increasing manner. Brake application should adjust vehicle deceleration in a way that will lead to a distance gap that will allow headway control by throttle modulation alone.

Every effort should be made to improve the forward-acceleration capability of the vehicle when it is under ACC control. The results indicated that the acceleration level used in increasing the speed of the ACC vehicle was not satisfactory in the opinion of most of the test drivers. Drivers did not want to slow down too much because they were concerned with how long it would take to get back up to the desired speed and desired headway time gap. They indicated that the resume rate of the system was the system's main weakness.

With regard to the buzzer that was used to warn the driver when the system was asking for its maximum deceleration authority, the responses were quite mixed. None of the drivers, however, considered the buzzer as a completely bad design feature. There were some drivers who did not like buzzers in general, and some drivers who thought that the features of this buzzer could be improved. Several drivers thought that the sound produced by the buzzer was too aggressive and unpleasant for a cautionary warning.

Since drivers are quite sensitive to changes in longitudinal acceleration, an ACC-with-braking system inherently provides a strong cue to the driver to pay attention to the forward scene when the brakes are applied. Nevertheless, warning can be given before the ACC vehicle decelerates substantially, thereby prompting the driver to intervene sooner. In summary, the results do not definitively resolve issues concerning intervention prompts or warnings. More work needs to be done in the area of collision warning.

Test exercises involving lay drivers are planned for next year. The testing process is expected to take place in stages. Testing will be performed first at a proving ground. Then, after developing confidence in the ability of lay drivers to handle the ACC-with-braking system (and also confidence in the reliability of the system), lay drivers will operate the system on a freeway route in the Detroit area near Metropolitan Airport. (The route and protocol would be very similar to the on-highway testing done during the first year using an ACC system without braking). During these test exercises data will be gathered to aid in assessing the driver's own headway management behavior as well as that of the ACC-with-braking system. Special emphasis will be placed on developing an understanding of when drivers choose to intervene on ACC by applying the brakes.

It is expected that the ACC system used in the course of next year's tests will be improved with respect to the acceleration rate for resuming speed. Also, it is hoped that means for a quicker detection of braking by the preceding vehicle can be used to expedite the braking response of the ACC system, thereby reducing driver anxiety. (The current design "waits" until the headway becomes relatively small before applying the brakes.) This will mean changes in the control algorithm beyond those described in this report. The goal is to provide drivers with a system that will be more satisfying than the one reported here.

1.0 Introduction

This document is the annual report for the third year of a cooperative agreement between the National Highway Traffic Safety Administration (NHTSA) and the University of Michigan Transportation Research Institute (UMTRI) to foster the development, evaluation, and deployment of forward crash avoidance systems (FOCAS). UMTRI's original partners in the FOCAS project are Automotive Distance Control Systems (ADC) GmbH (a joint business venture of Leica and Temic to develop and market advanced distance control technology), Haugen Associates, and the Michigan Department of Transportation. This year an agreement with ITT Automotive, Inc. expanded the research and development capabilities of the FOCAS project to include the use of electronically controlled braking.

The overall goal of the FOCAS program is to facilitate the development of application systems that supplement the forward crash avoidance performance of drivers. To aid in achieving this goal, the research program seeks to develop evaluation tools, methodologies, and knowledge base as needed to expedite the development of adaptive cruise control (ACC) and forward crash avoidance (FCA) systems including forward collision warning (FCW) systems.

The research work done in the first and second years provides a foundation for the work performed in this third year. The annual report for the first year (see reference [1]) contains detailed information on (1) the characteristics of a baseline ACC system, (2) the performance of the baseline system, and (3) the human factors and engineering aspects of problematic situations related to ACC driving. The second annual report [2] covers (1) test results and systems-development experience for more complex ACC features including driver-adjusted headway and (2) methodology and findings pertaining to a warning function based upon a low-deceleration cue. Specifically, the second annual report presents detailed information on

- driver-adjustable headway time,
- observations concerning drivers (hunters, flow-followers, and gliders),
- neural net methods for finding driving episodes,
- an audio prompt for ACC intervention (crash warning),
- implementation of a brake-assisted low-deceleration cue,
- use of a borrowed ACC test vehicle with 0.18 g deceleration authority.

The technology-related work for the third year is focused upon the addition of braking to an UMTRI prototype of an ACC system. The objective of this work is to provide test results and system-development experience showing the engineering and human factors issues posed by braking as a supplement to ACC or within a medium-deceleration crash avoidance function.

The next section of this report describes the engineering considerations behind a new test vehicle that incorporates both throttle and brake controls. An initial study of the human factors issues was conducted through evaluation of this vehicle by a number of researchers who are familiar with ACC systems. Section 3 presents results that are based upon the judgments of those experts. The report concludes with sections summarizing the findings of this year's work and describing the plans and expectations for next year's work.

2.0 Experience Developing an ACC System With Braking

2.1 Overview of the Control System

The control system implemented this year differs from that exercised earlier by the manner in which the service brakes were utilized. During the second year, the brakes were utilized strictly as a warning cue to the driver. The ACC functionality implemented during the third year employs braking in a continuous manner as an integral part of headway keeping. The system's engagement status is not disrupted when the brakes are activated. However, the feature by which disengagement results from driver application of the brake pedal is still maintained. A detailed description of the rule-based algorithm and the associated hardware for this system are presented later.

Figure 1 illustrates the control architecture of the new ACC system that incorporates both throttle and brakes. In a generalized form, the control of headway involves three elements: a commander, a controller, and the controlled plant – the vehicle. These three elements comprise a control loop aimed at achieving the system's goal.

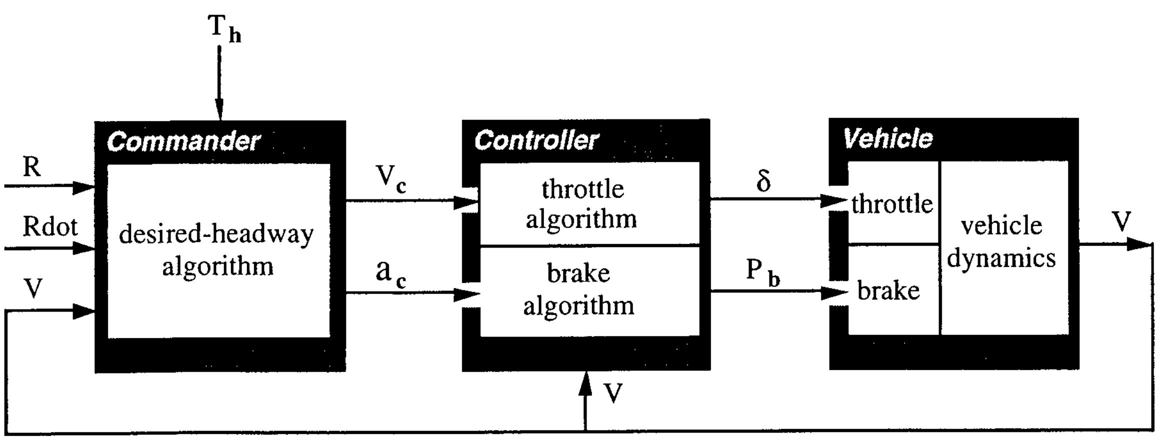

Figure 1. Control architecture for the ACC system with braking

The commander encompasses the main objective of the ACC system, which is to reach a planned, desired headway. As in past years, the desired-headway algorithm employed four variables as its inputs: the actual range to the preceding object in its path (R), the rate of change of that range (Rdot), the velocity of the host vehicle (V), and a setting that represents the desired headway time (T_h). The commander evaluates its inputs and determines the action that needs to be taken. As shown in Figure 1, the outputs of the commander are two values: a desired speed (V_c) of the ACC-equipped vehicle, and an acceleration value (a_c) that should be employed in attaining that speed. According to the commander's output, the desired-headway algorithm might require the speed to increase ($a_c > 0$), to decrease ($a_c < 0$), or to remain unchanged ($a_c = 0$).

Hardware limitations, as explained later, prohibited us from controlling the rate at which the vehicle accelerated (i.e., sped up). The deceleration rate, however, could be fully regulated by the brakes. Practically, therefore, in this application acceleration commands that were positive (i.e., $a_c > 0$), were meaningless. If no speed change was needed the algorithm command was $a_c = 0$, and if deceleration was needed the algorithm command was some negative value of a_c.

The controller translates the output commands from the commander into control actuation. The controller consists of two distinct modules: the throttle algorithm and the brake algorithm. The throttle algorithm converts the value of the desired speed into a throttle position (δ). This algorithm is part of the OEM's engine controller. The brake algorithm, which was developed by UMTRI, converts the desired deceleration value into a brake-pressure command (P_b). Both the throttle module and the brake module utilize the velocity of the host vehicle to determine the throttle and brake commands respectively.

The ACC-equipped vehicle is a plant whose velocity is regulated through two mechanisms, namely the throttle (engine), and electronically controlled brake system. The throttle and brake manipulations determined by the controller cause the velocity to change in a manner that is consistent with reaching the headway-control objective. In philosophical terms, when the system succeeds in making the vehicle act as planned, the headway objective is obtained.

The control architecture described above encompasses a diverse set of elements. Some are off-the-shelf OEM items (such as the vehicle itself), some are OEM development prototypes (e.g., range sensors and brake actuator), and others are project-specific development items (such as the control software). All these elements were integrated to attain a test vehicle having the ACC-with-brakes functionality. The elements are individually described in the following sections.

2.2 The Host Vehicle

During the first two years of the FOCAS project, the experience in developing, installing, and evaluating ACC and crash-avoidance-oriented systems was primarily based on the use of a 93 Saab 9000 turbo. This experience is summarized in [1] and [2]. Additional experience was gained by having UMTRI's professional staff use an ACC-equipped Volvo 850 GL that employed braking. This additional experience is also summarized in

[2]. Since UMTRI's testing capability of the Volvo was limited, and we were not in a position to alter any of the design parameters of its ACC system, UMTRI (together with ADC) entered into an agreement with ITT Automotive, Inc. Through this agreement, ITT Automotive supplied the partnership with a 96 Chrysler Concorde that was dedicated to the testing of ACC with brakes, using an ITT smart-booster package, described later.

The Chrysler Concorde is a five-passenger sedan which belongs to the family of Chrysler LH-platform cars (see Figure 2). This family also includes the Dodge Intrepid, Eagle Vision, Chrysler New Yorker and Chrysler LHS.

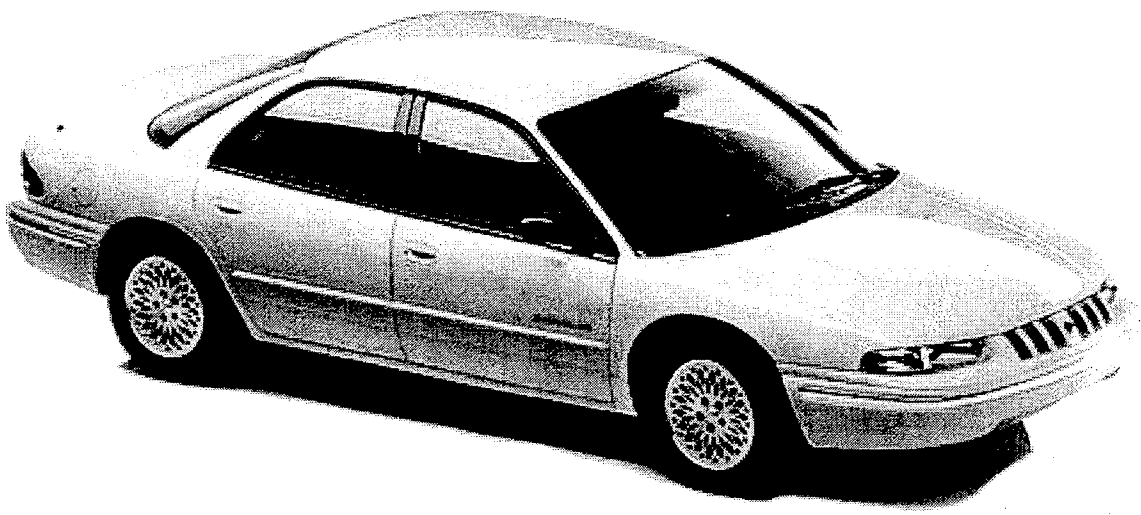

Figure 2. Chrysler Concorde

The primary motivation for using the Chrysler Concorde as the test vehicle platform was based on UMTRI's and ADC's prior experience with integrating an ACC system and installing instrumentation onto this model of car. This experience is based on the recently completed field operational test (FOT) [3]. The vehicle is equipped with a 3.5-liter engine (214 hp), four-speed automatic transmission, and power-assisted four-wheel disc antilock braking system. In order to allow *brake by wire*, ITT modified the braking system from its OEM configuration by installing their smart booster, described below.

2.3 Headway Sensors and System Electronics

The ACC system includes the ADC-supplied package which is comprised of headway sensors, electronic components box (EBOX), and vehicle application controller (VAC) box. Each of these items is described below.

ADC infrared range sensors were supplied with an installation kit which includes an adjustable mounting. Once the sensor is firmly clamped into this mounting, it is possible to vary its alignment using several adjustments. Installing the sensors in the vehicle involved modifying the adjustable mounting, affixing it to the vehicle's front bumper, and modifying the grill to accommodate the sensors. All the sensor-mounting activities have been carried out by UMTRI.

The adjustable mounting includes a subframe onto which the sensor is attached. This subframe can be slid up or down, and it can also be pitched and yawed. To accommodate installation in the grill between the bumper and the radiator, it was necessary to modify some parts of the adjustable mounting. Special brackets were fabricated and welded to the bumper frame, and the modified adjustable mountings were bolted onto these brackets.

Special openings were cut in the grill to accommodate the sensors. Also, provisions were made to allow access to the adjustment screws of the mountings without removing any parts. The installed sensors are shown in Figure 3. The transmitter and receiver of the so-called sweep sensor (defined below) are shown on the driver's side of the grill; those of the so-called cut-in sensor are shown on the passenger's side of the grill. The sensor's coverage areas are illustrated in Figure 4.

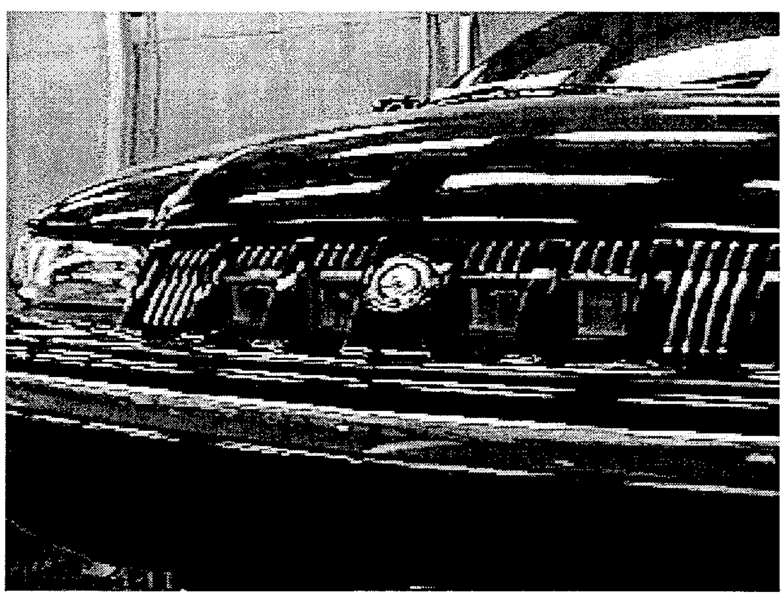

Figure 3. Sensors installed in the grill

The sweep sensor is a steered laser-based infrared beam which is directed left or right based upon computations from a solid state gyro which dynamically responds to yaw rate. The sweep sensor detects targets in the far field (6 to 150 meters ahead). The cut-in sensor has a fixed beam and limited range, being used to sense vehicles that might cut in close to the front of a test vehicle (within the range of 0 to 30 meters). Both sensors operate by transmitting pulses of infrared light energy at a wavelength of 850 nanometers and a frequency of 10,000 pulses per second. The time of flight for an echo pulse to be received is used to determine range and range rate to a target vehicle.

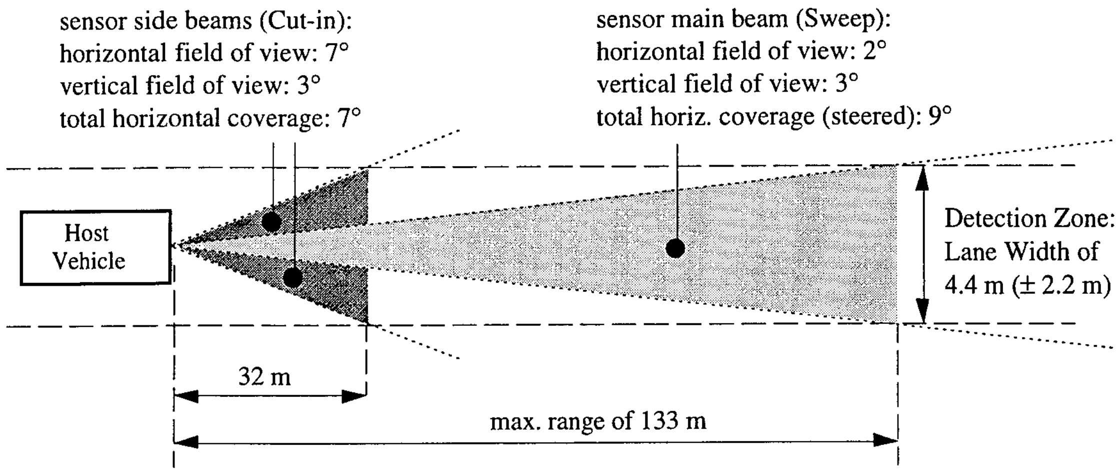

Figure 4. ODIN4 sensors coverage areas

The EBOX contains the solid state gyro, the system power supply, electrical interfaces to the sensors, an external power supply, a Leica diagnostic connection, and CAN bus and RS232 interfaces.

The VAC contains software code and algorithms, including the UMTRI code and algorithms, used to provide the ACC control functions.

2.4 The Smart Booster

The key new feature of the test vehicle is ITT's smart booster. This device is a direct replacement for the conventional vacuum booster supplied as original equipment on this car, and is a preproduction prototype that has been years in the development by ITT Automotive. The smart booster receives serial digital data as a brake-pressure command, and it delivers four-wheel-brake application at the commanded level of hydraulic line pressure. From a mechanical point of view, the smart booster controls brake pressure by means of valving internal to the vacuum booster assembly, admitting vacuum as needed to reach the desired braking pressure by controlling the travel of the master cylinder piston.

Pursuant to a nondisclosure agreement with ITT Automotive, this section will not discuss detailed technical information pertaining the smart-booster design. However, the characteristics and operational features of the device are described as they emerged from testing the installed smart booster, and as they were seen to affect the functionality of the completed ACC system.

Figure 5 provides a schematic overview of the smart-booster implementation in the ACC test vehicle. Using Figure 5 as a road map, the various responsibilities of the FOCAS partners in implementing the overall system is further clarified. That is, ITT installed the smart booster into the vehicle, including the interface to the booster's electronic control unit (ECU); ADC designed the software interface to the control-area-network (CAN) communication to the smart booster and provided the sensor system; UMTRI developed and programmed the headway and brake algorithm into the VAC unit and was responsible for the integration of the complete ACC-with-brakes package into the vehicle so as to ensure its functionality. Both ITT and ADC provided UMTRI with technical support as needed during the installation.

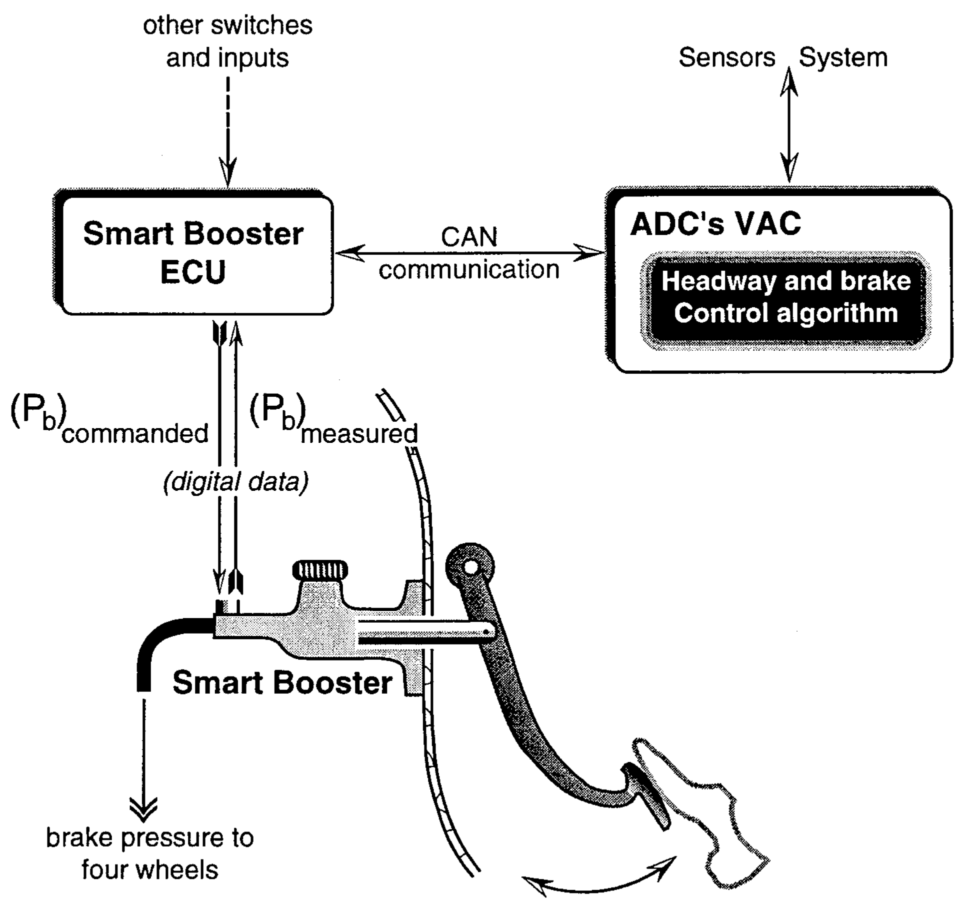

Figure 5. Smart-booster implementation

Once the installation was complete, calibration tests were commenced. The primary purpose of these tests was to establish a relationship between brake pressure and the ensuing deceleration rate. Since the desired-headway algorithm computes a deceleration command (a_c), and the interface to the smart booster requires a brake pressure value (P_b), it was necessary to characterize the relationship between the two.

In order to obtain that relationship, a total of 24 tests were performed. These tests encompassed four brake-pressure values (5, 10, 15, and 20 bars), each of which was applied at three different rates: 10, 20, and 30 bar/sec. Each of the twelve cells of the test matrix was performed twice. All the braking tests were from an initial speed of 50 mph (80 km/h). The average result obtained from each test pair is plotted in Figure 6.

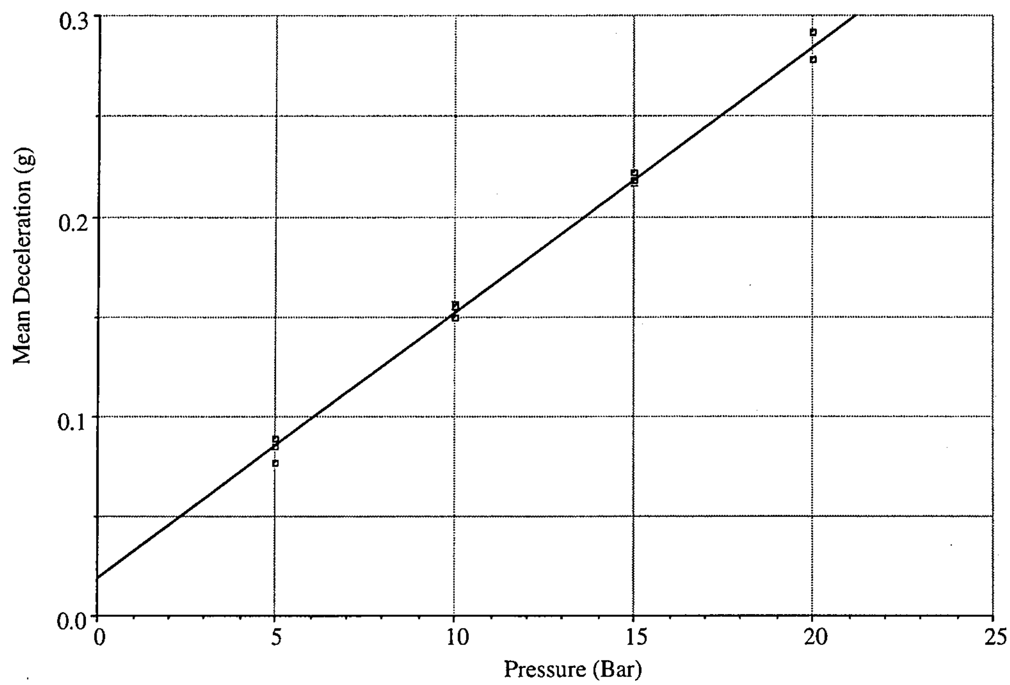

Figure 6. Pressure-Deceleration characteristics

As observed in Figure 6, a straight-line relationship exists between a_c and P_b. That relationship is given by equation (1). Note that this relationship is defined only for the case of deceleration with braking, or for $a_c < 0$.

$$a_c = -0.0189 - 0.01328 \cdot P_b \tag{1}$$

Other considerations that were investigated during the calibration testing of the smart booster were

- jerk levels (rate of change of deceleration) that would apply for different increments in brake-pressure command,

- brake-pressure transient-response characteristics,
- the selection of practical upper bounds for automatic application of braking by the ACC controller,
- system provisions that properly distinguish between driver-applied and ACC controller-applied braking.

A typical vehicle response to brake command is depicted in Figure 7. The results shown are for a braking test, using the brake-by-wire application of the smart booster, at a level of 10 bar from 65 mph (104 km/h). Following an initial overshoot of approximately 0.5 bar, a constant brake-pressure value is established at approximately 0.5 bar below the nominal commanded value. This initial overshoot and the rate of its subsequent decay help in making the braking action both clearly perceptible and yet reasonably smooth to the driver.

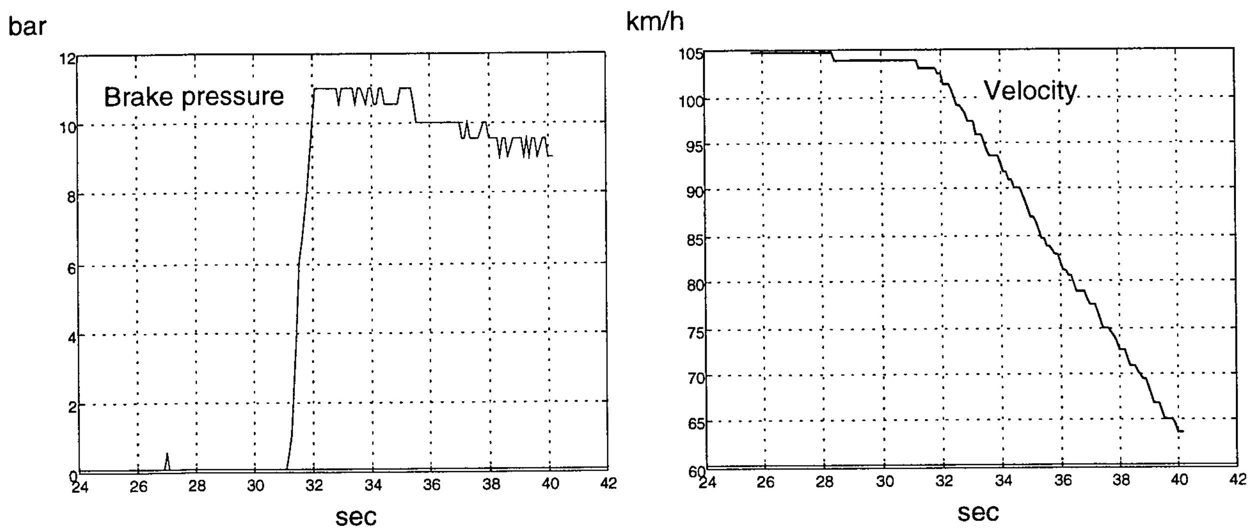

Figure 7. Typical braking response

An additional important characteristic of the smart booster is that it does not respond to pressure commands below 4 bar (that is, pressure commands between 0 and 4 bar are ignored). During characterization testing it was seen that the deceleration attained in response to a brake-pressure command of 4 bar was 0.07 g. At the other extreme, the smart booster can apply effectively full-braking levels of hydraulic pressure. For the ACC application, however, it is clearly appropriate to limit the braking-authority level to more modest values. In this project, the maximum-brake-pressure command was limited (through software) to a value of 15 bar, corresponding to a maximum deceleration rate of 0.22 g. This limitation was introduced because

- the potential for a false activation at a higher deceleration rate is believed to pose a safety risk for operating on public roads,
- a conservative approach seemed appropriate for the first field trials using an unfamiliar device that was, itself, a prototype,
- no more than 0.22 g was thought to be needed for the intended use in this ACC application; an emergency crash-avoidance functionality was not intended.

Next, the characteristics of the smart booster and the vehicle's response to various levels of braking were incorporated into the desired-headway algorithm in the commander and into the controller's brake algorithm (see Figure 1).

2.5 Braking Rules and Their Implementation

The basic design of the headway-control algorithm is discussed in detail in Section 2.2 of the first-year report [1]. The system sought to obtain the desired headway by means of throttle modulation and, if needed, a transmission downshift. The algorithm commanded various speed values (V_c), which in turn were translated by the OEM engine controller into throttle manipulation. When acceleration was called for, throttle setting was increased, and when the vehicle was required to slow down, the throttle was reduced. At full coastdown (i.e., throttle closed to idle), the maximum deceleration attained at highway speeds by the test vehicle was approximately 0.05 g. If more deceleration was called for, the transmission downshifted, causing the deceleration level to reach approximately 0.07 g. Brakes were not applied automatically to control speed.

During this past year, the introduction of a smart-booster capability has served to expand the functionality of the ACC system so as to automatically handle many headway conflicts that would have otherwise caused the driver to intervene. This section presents the concepts through which braking was incorporated into the ACC system, using a rule-based algorithm for engaging the smart booster.

To begin, it was noted that participants in the FOT study [3] expressed resistance to the concept of automatic-brake actuation. Drivers expressed this outlook both through questionnaires and during focus-group discussions. They expressed concern regarding issues such as overall safety, a possible mismatch between their level of faith in the system and its actual control limitations, comfort, and the general human concern of "I don't know what the machine is going to do." It was clear that for drivers to accept an ACC system incorporating brakes, and for them to have an overall positive experience when using such a system, special consideration should be made to address their concerns.

There were several guiding concepts in the design of the system, as follows:

- Safety — The system must not be allowed to operate automatically beyond a prescribed envelope of range and speed. To some extent, that boundary may be set by the driver. Also, the driver must be informed when the system involuntarily ceases to be engaged. In addition, throughout the design, a conservative approach should be adopted. It should be noted, however, that this last guideline may conflict at times with other concepts employed in the design (see bullet item "Compatibility and Adjustability" below).
- Priority of Driver — The driver's input always prevails. The system must be able to recognize and suitably prioritize longitudinal control inputs made by the driver and those issued by the control algorithm. That is, if the brakes are engaged by the ACC controller and the driver depresses the accelerator pedal, the brakes should promptly disengage and allow the car to accelerate. Conversely, if the ACC system is maintaining speed, or even accelerating, and the driver depresses the brake pedal at the same time, the throttle should drop and braking should commence. Also, if the brakes are engaged at some level by the ACC system and the driver depresses the brake pedal to obtain a higher deceleration rate, the brakes should respond at the higher braking level.
- Compatibility and Adjustability — The system's automatic actions should be compatible with those that would have been otherwise taken manually by the driver. The design of the system should provide adjustments, so as to accommodate different driving styles. Clearly, the concept of compatibility and adjustability can conflict to some degree with safety goals. That is, it may not be feasible to adopt a conservative design approach and still accommodate aggressive driving styles. Furthermore, this concept is most challenging to implement because the scope of individual driving styles is very wide.
- Comfort — Braking application should be smooth. The transition from acceleration to coastdown and to application of the brakes should not be jerky. The operation of the system within its boundaries should enhance the comfort of the passengers. Notwithstanding the comfort objective, however, safety concerns may take precedence over those of comfort (as noted further, below).
- Reassurance and Lack of Ambiguity — When acting on headway conflicts, the system should communicate a clear and consistent control strategy to the driver by means of its overall set of responses and displays. The driver should not be subjected to anxiety, in anticipating how the system is going to respond. Moreover, the system's response should be predictable. The system should also

be such that lay drivers can easily learn its operation and the behavior to be expected when headway conflicts present themselves.

The starting point of the algorithm-development work was the design used during the first two years of FOCAS project and the ACC field operational test. It is described in detail in [1] and [3]. The discussion in the following few paragraphs serves as a summary of that design, and it is provided to introduce the braking algorithm and rules.

The basic design is illustrated in the range-versus-range-rate diagram shown in Figure 8. The control objective appears as the straight line in the figure. The slope of that line, –T, serves as a control-design parameter as indicated by the following equation for the control objective:

$$T \cdot R_{dot} + R - R_h = 0 \tag{2}$$

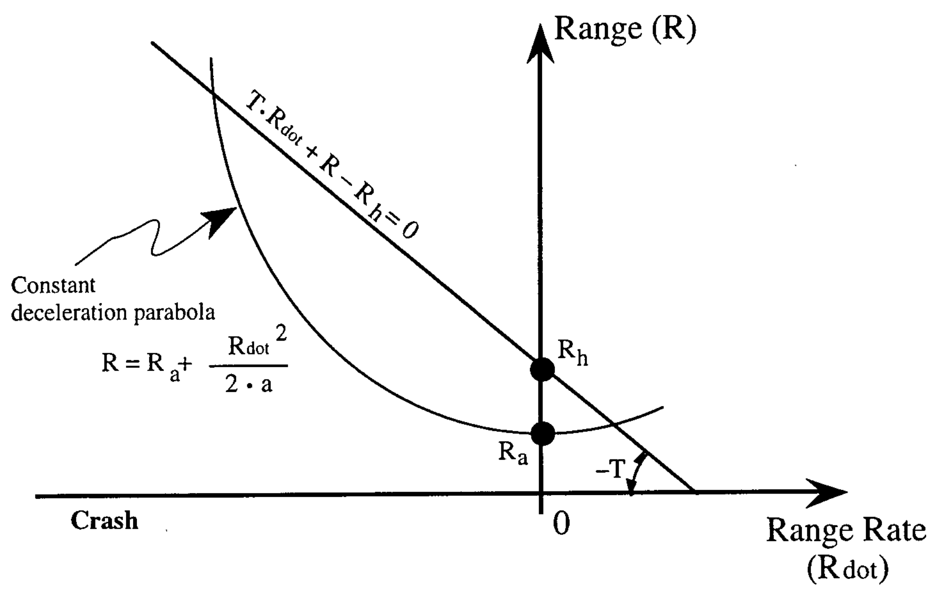

Figure 8. Range rate versus range

The parameter T represents the time constant in a first-order differential equation. Equation (2) indicates that the objective of this control concept is to make the two-vehicle system (which includes the host vehicle, the controller, the commander, the sensor, and the impeding vehicle) act like a first-order differential equation with a stable equilibrium point at $R = R_h$ and $R_{dot} = 0$. When operating on or near the surface described by equation (2), the range to the impeding vehicle approaches R_h in an exponential manner, which is exceedingly smooth.

When operating at points off of the surface described by the control-objective function (equation (2)), the system uses the available control authority to move as quickly as it can to the vicinity of the surface described by the control-objective function.

The intercept at $R = R_h$ is the ultimate objective for the ACC-equipped vehicle. The value of desired headway during steady following is a linear function of V_p, the velocity of the preceding vehicle, namely,

$$R_h = V_p \cdot T_h \tag{3}$$

where T_h is the desired headway time, and V_p is expressed by $V_p = V + R_{dot}$. The parabola in Figure 8 represents a trajectory of constant deceleration a (assuming that V_p is constant) in the range versus range-rate space. The intercept of the constant deceleration parabola, at $R=R_a$, can be viewed as a design factor which may vary from some arbitrary headway threshold all the way down to zero. The higher the parabola's deceleration rate, the flatter the parabola becomes. The deceleration rate may be chosen as needed to satisfy various design purposes.

The basic design incorporates a methodology which is conceptually similar to that of a sliding control, in the sense that the straight line (in Figure 8) serves as a type of sliding surface. The expression for the velocity command, based on this "modified" sliding-control methodology, is given by:

$$V_c = V_p + \frac{(R - R_h)}{T} \tag{4}$$

This velocity command is one of the outputs of the desired-headway algorithm depicted in Figure 1.

In both the FOT and the early FOCAS designs, the value of "a" was set at the coastdown deceleration of the vehicle. Whenever the range and range-rate data from the sensors fell below that parabola, added deceleration was provided by downshifting the transmission. However, downshifting provided additional deceleration of only 0.02 g. With the availability of the ITT smart booster, the control authority of the algorithm was significantly expanded, such that headway conflicts that would have saturated the throttle-plus-downshift controller could now be managed. As was shown in Figure 1, a new commander module which computes a desired deceleration (a_c) is now incorporated into the desired-headway algorithm. The computed value of desired deceleration is used by the braking algorithm to control the brakes.

Several control strategies and algorithms to incorporate automatic braking and to implement the concepts described above were developed and subjected to experimental evaluation. Some involved a single braking level that was invoked when the range and range-rate coordinates dropped below the coastdown parabola (similar to the concept for invoking downshifting, but with a higher deceleration level). Other algorithms involved two discrete braking levels when operating within different zones below such parabolas. A few algorithms involved a simplified longitudinal model of the vehicle for computing V_c in the sliding-control methodology (instead of using equation (4)). Several other algorithms were based on the basic design employed in the FOT, with gains that could be adjusted and with various schemes for a gradual brake application. Each algorithm was programmed into the VAC and a short sequence of characterization tests was performed with the test vehicle. The test procedures were as described in [5] and they were aimed at allowing both qualitative and quantitative evaluation of such ACC systems.

A design that was found to address the guiding concepts in a reasonably balanced way is illustrated in Figure 9. This design is based on combining the desirable features of various algorithms that were developed, as their respective qualities emerged during the characterization tests.

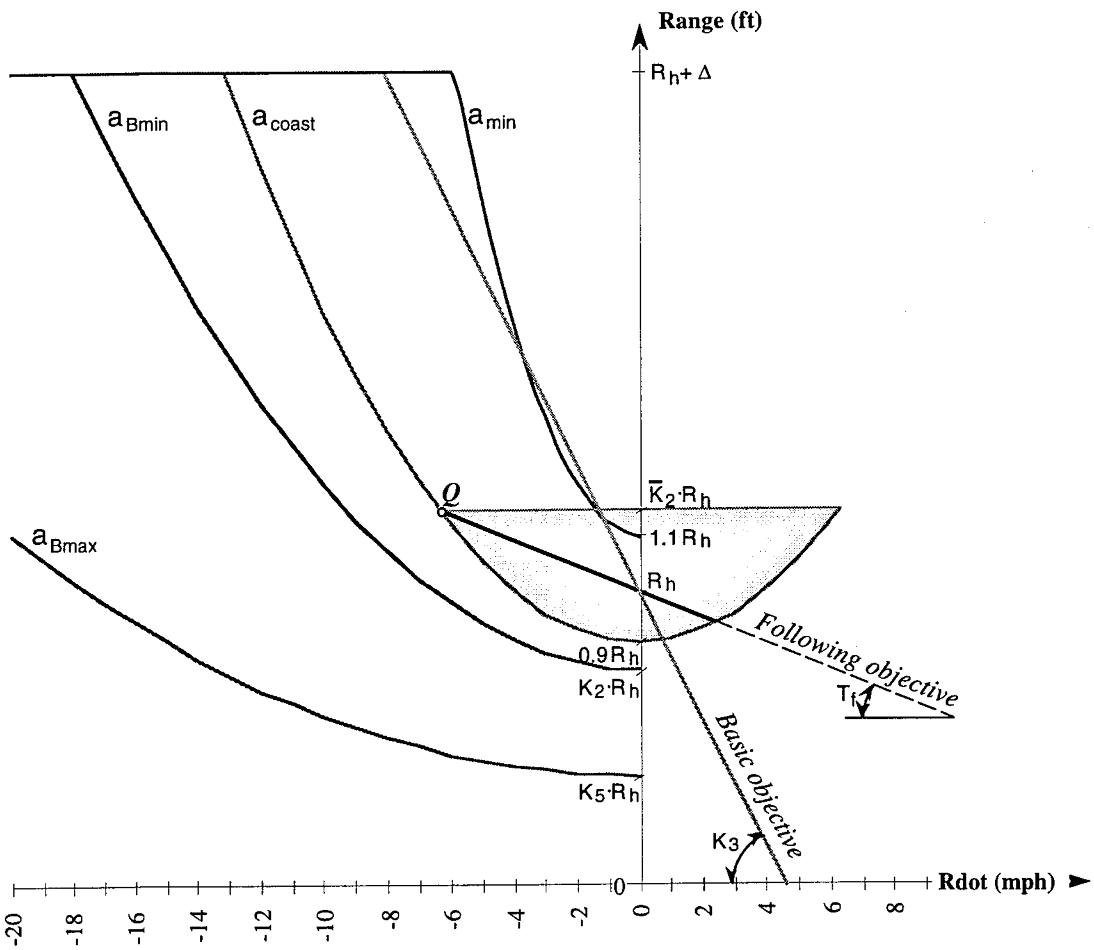

Figure 9. Brake rules and control algorithm

The basic control objective in this approach is similar to that used in the previous FOCAS test platforms and in the FOT; in Figure 9 it appears as the straight line with slope K_3. This slope is a parameter that was made adjustable via a specially developed computer-software interface so as to allow its modification even while the vehicle is being driven. Additional parameters were incorporated into the controller's design and in the following discussion they will be appropriately noted. This parametric flexibility allows the researcher to explore a wide range of operational settings in the course of a test drive and to immediately experience their effect. It is convenient to explain the other elements in Figure 9 by simply stating the following control rules:

- When engaging a new target for the first time, the system will respond to it only after its range, and range-rate coordinates (hereafter termed the *operating coordinates*) arrive within the area bounded by the maximum range limit (R_h+Δ), the constant-deceleration parabola labeled a_{min}, and the vertical Range axis (see shaded area in Figure 10). The desired-range value, R_h, is computed per equation (3); Δ is a fixed range margin (40 m, 132 ft); and a_{min} represents a design value for the minimum-control deceleration to be employed during headway conflicts. In this controller, a_{min} was selected to be 0.01g.

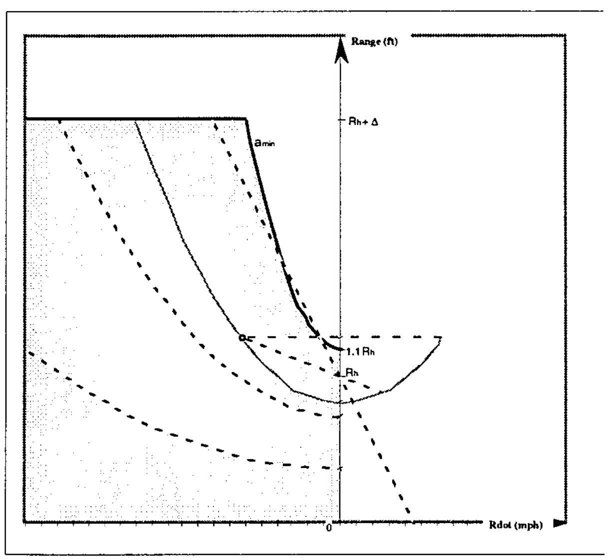

Figure 10. New-target engaging zone

- If the operating coordinates fall between the constant-deceleration parabolas labeled a_{min} and a_{coast} in Figure 9 (but above the horizontal line that connects to the point labeled "*Q*"), the current velocity is maintained (i.e., Vc = V). The variable a_{coast} represents the nominal coastdown deceleration of the vehicle. It has been defined as 0.04g based on the results of characterization tests.

- If the operating coordinates fall between the constant-deceleration parabolas labeled a_{coast} and a_{Bmin}, the system commands coastdown (without braking). The variable a_{Bmin} represents the minimal deceleration achievable by the electronic braking system and was set at 0.07g (see discussion in section 2.4).
- The shaded area in the center of Figure 9 defines the *following* zone. This zone is bounded by the constant-deceleration parabolas labeled a_{coast}, and the horizontal line that crosses the Range axis at $\overline{K}_2 \cdot R_h$. This line intersects the a_{coast} parabola at the point labeled "*Q*". The value of $\overline{K}_2$ is determined by the value of the parameter K_2 so as to be symmetrically located about R_h (i.e., if $K_2 = 0.8$, then $\overline{K}_2 = 1.2$, etc.). Note that the following zone itself is not symmetrical about R_h: it spans from a minimum value of $0.9 \cdot R_h$, to a maximum of $\overline{K}_2 \cdot R_h$. Inside the following zone, brakes are not used but the gain of the speed command is increased in an attempt to get a quicker throttle response, and therefore improved following characteristics. When the operating coordinates are inside the following zone, the controller uses point, *Q*, and the range, R_h, to compute the value of T_f. The *following objective* is then used to compute a speed command:

$$V_c = V_p + \frac{(R - R_h)}{K_7 \cdot T_f} \tag{5}$$

  where K_7 is a gain factor.
- If the operating coordinates fall between the constant-deceleration parabolas labeled a_{Bmin} and a_{Bmax}, the system commands partial braking. The variable, a_{Bmax}, represents the maximum deceleration authority of the brakes, set at a value of 0.22 g. The parameters K_2 and K_5 determine where the parabolas, a_{Bmin} and a_{Bmax}, cross the range axis, respectively. These parameters represent design concepts aimed at providing a range of answers to questions such as "How much of the desired headway are we willing to sacrifice for the benefit of smooth driving before we activate the brakes?" and "Once we start braking, how much more headway are we willing to sacrifice, before we go to the maximum braking authority?" Given the operating coordinates, the system executes an interpolation scheme to determine a level of partial braking that will bring the ACC-equipped vehicle to a range between K_5R_h and K_2R_h.
- When the operating coordinates are at or below the constant-deceleration parabola labeled a_{Bmax}, the system commands its programmed full-braking level (i.e., 15 bar, 0.22 g).

- In the positive-Rdot quadrant of the space depicted in Figure 9, the system employs no braking. The commanded velocity in that area (and also throughout the rest of the Rdot-Range space which was not covered by the rules above), is determined by the *basic objective*:

$$V_c = V_p + \frac{(R - R_h)}{K_3} \qquad (6)$$

  Note that the basic objective in equation (6) and also the following objective (shown above in equation (5)), are based on the same original form of first order differential equation used as the control objective in the earlier FOCAS work (see Figure 8). These objectives differ from each other only by the gain values used.

Another adjustable parameter that was used during the system-development stage and the initial testing is a jerk-rate limit which simply governs the rate at which pressure commands are changed, thus avoiding the uncomfortable jerk response that the smart booster is capable of achieving. Incorporation of adjustable parameters into the various braking and velocity-control rules employed in the new ACC test vehicle, allowed experimentation with settings and the identification of values that are acceptable to drivers.

2.6 Throttle Control

Throttle control, as described above, begins with the commander sending a desired-speed command (Vc) to the controller. The algorithm that directly controls throttle displacement (δ) to achieve that speed, however, actually resides within the OEM engine control unit. Accordingly, it was not possible to modify or prescribe the rate at which the throttle would respond to commanded speed, since throttle response is determined by the design of the cruise control module existing in the Chrysler Concorde. The consequences of this constraint will be discussed in detail in section 3.0.

Although the cruise control module could not be modified, an effort has been made to characterize and document the nature of the throttle response. Figure 11 shows typical throttle and vehicle speed responses to a desired-speed input command. The illustrated responses follow a step input of speed from approximately 60 mph (96 km/h) to 80 mph (128 km/h). On the right side of the figure, the commanded speed and the vehicle response speed signals are labeled Vc and V respectively. The left side of the figure shows the throttle's response. The corresponding nominal acceleration was computed and found to be 0.028 g. Similar acceleration rates were computed for maneuvers which involved other speeds. Such characteristic throttle responses were used in the course of designing the control algorithm so as to account for the throttle's predominant sluggishness.

Since it was not possible to redesign the Chrysler cruise control, this part of the system was simply treated as a black box that could not be changed. Nevertheless, while the acceleration performance was not excellent, it was adequate for causing the vehicle's speed (V) to eventually approximate the desired speed (Vc) and thereby to satisfy the headway-control goal.

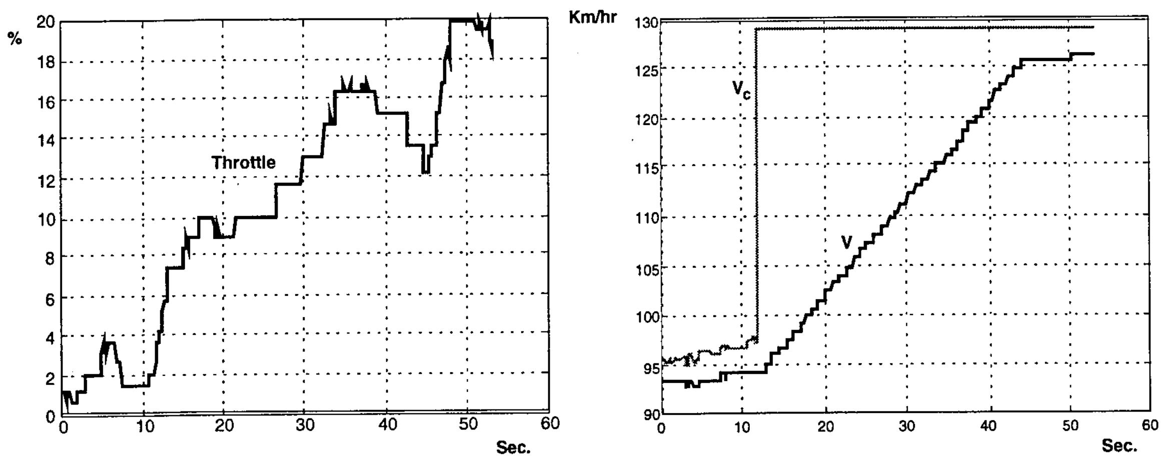

Figure 11. Throttle and speed response

2.7 Warning Features

The ACC system that was developed in the past year represents an advancement from the ACC systems developed previously. In none of the prior work, however, did the ACC controller incorporate any deliberate provision to suggest a manual intervention on ACC control. During the past year, this additional step was taken by integrating an active warning function into the system's design. A simple, yet unequivocal rule was implemented to activate a warning buzzer.

The rule, as it was introduced to the drivers who experimented with the car, was "Whenever the conflict is such that the ACC system is asking for its full level of brake application, the buzzer sounds." Stated in terms of the algorithm design (see Figure 9), the buzzer was activated when the operating coordinates were at, or below, the constant-deceleration parabola labeled, a_{Bmax}, and the system had commanded its programmed full-braking level (i.e., 15 bar, 0.22g).

As it was explained to the drivers, actuation of the buzzer does not necessarily mean that a crash is imminent or even that intervention is required. Rather, the purpose of the warning buzzer is to call the driver's attention to the forward scene. The driver then needs to evaluate the situation and to make a decision regarding the need for further action. This approach is in concert with the view that under ACC driving, the driver must maintain supervision of the ACC system. ACC does not constitute a fully autonomous driving system. In tests conducted here, the warning feature was used to help select attention-getting thresholds and to evaluate driver's acceptance or rejection of the warning feature.

2.8 Instrumentation

The instrumentation package installed in the new test vehicle is based on the system which was developed for the field operational test. This package is described in the FOT's interim report [3]. For the FOCAS application, however, the video system and the automatic cellular calling system were not installed since a researcher was always present when the car was driven by a lay driver.

The entire data-acquisition system (DAS) is mounted in the forward portion of the vehicle's trunk. Figure 12 shows a block diagram of this system, showing that it consists of three subsystems:

- power, interface, and control
- data computer
- GPS

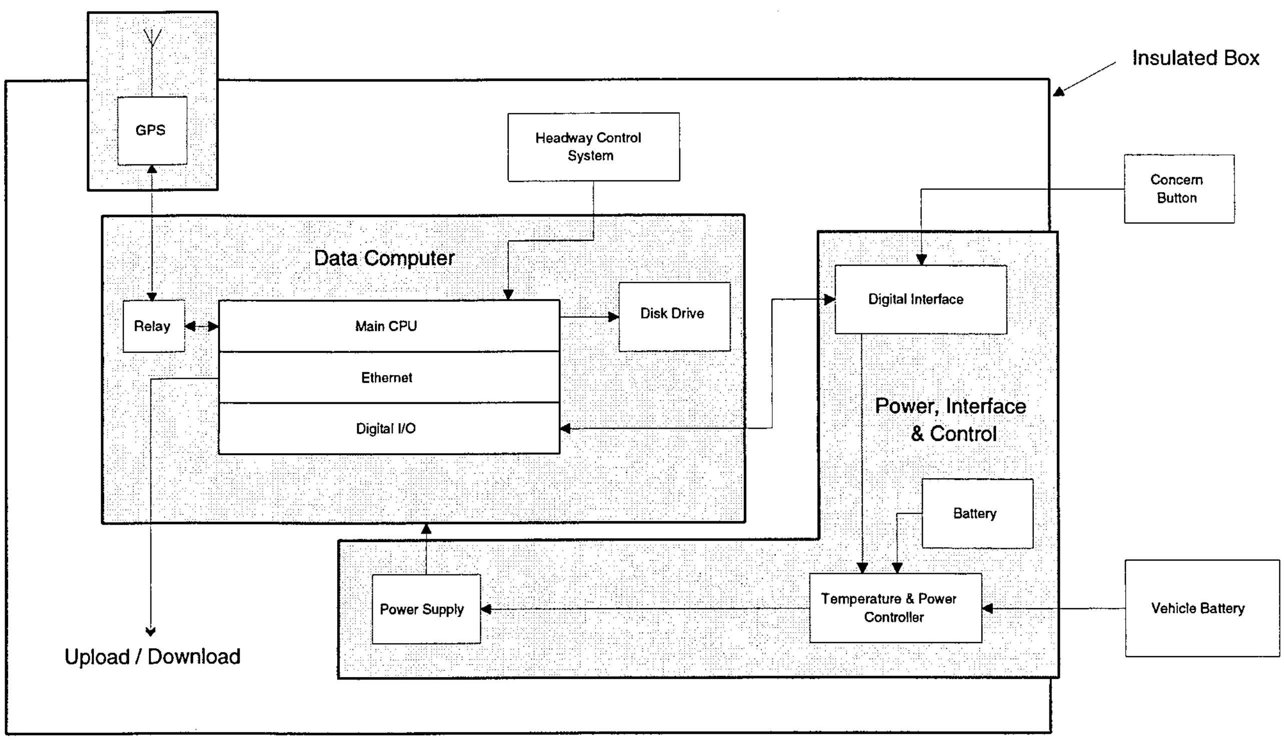

Figure 12. Data-acquisition-system hardware

The DAS components are mounted in a chassis which houses the data computer and associated peripherals (see the items on a shaded background in Figure 12). The chassis also supports the VAC and EBOX elements of the headway-control system. An insulating Styrofoam structure encloses the electronic package and provides a thermally stabilized environment. This covering is modified to suit the thermal demands of each season.

Data collection within the instrumentation package proceeds in simultaneous formats, as follows:

- Time-history sampling of primary and derived variables at 10 Hz in floating point form, for continuous variables, and in binary (true/false) form for logical variables (these data are stored on the disk drive that is part of the data computer).
- real-time processing of data variables provide histograms and counts of pertinent events.

The onboard computer not only controls the gathering of data but also conducts on-line data processing. The computer calculates the derived floating-point and logical variables and it sorts the time-history data into bins in order to form floating-point and logical histograms.

Several stages exist for the processing of test data, namely: (1) validation of data integrity and system operation, (2) interpretation of the data, and, (3) quantification of system performance.

The data-computer system collects and records data from the headway-control system, the vehicle itself (via the headway-control system), and the GPS system. The data are organized by trip (defined from ignition on to ignition off). The data-computer system also performs on-line data processing to generate derived channels, histograms, and summary counts. The processed variables are acquired from the Leica sensor, the control algorithm, the automotive electronics bus, the man-machine interface, and the GPS.

When the vehicle is started, the interface and control system activate the data computer which turns on the GPS. The GPS system sends (via a RS-232 serial line) encoded position and velocity packets every time it computes a new position. The data computer decodes these packets, calculates a grade estimation and heading from the velocity information, and stores the time, latitude, longitude, altitude, grade, and heading to a position file. The GPS time at the moment of power up is used to set the data-computer clock.

The headway controller sends (via an RS-232 serial line) an encoded packet of information every 0.1 seconds. The data computer decodes this packet and extracts data from the appropriate sensor and vehicle information channels. Derived variables are then calculated and selected information is logged to a time-history file. Some logical channels are logged to a transition file. Each transition-file record indicates a channel number, the time of the false-to-true transition, and the duration over which the signal was true.

2.9 Driver's Interface

An integral part of the ACC system is the driver interface. The interface used for conventional cruise control was maintained in its OEM configuration and incorporated into the control of the ACC system. However, several new elements were added in order to accommodate use of the ACC system. The driver interface is illustrated in Figure 13.

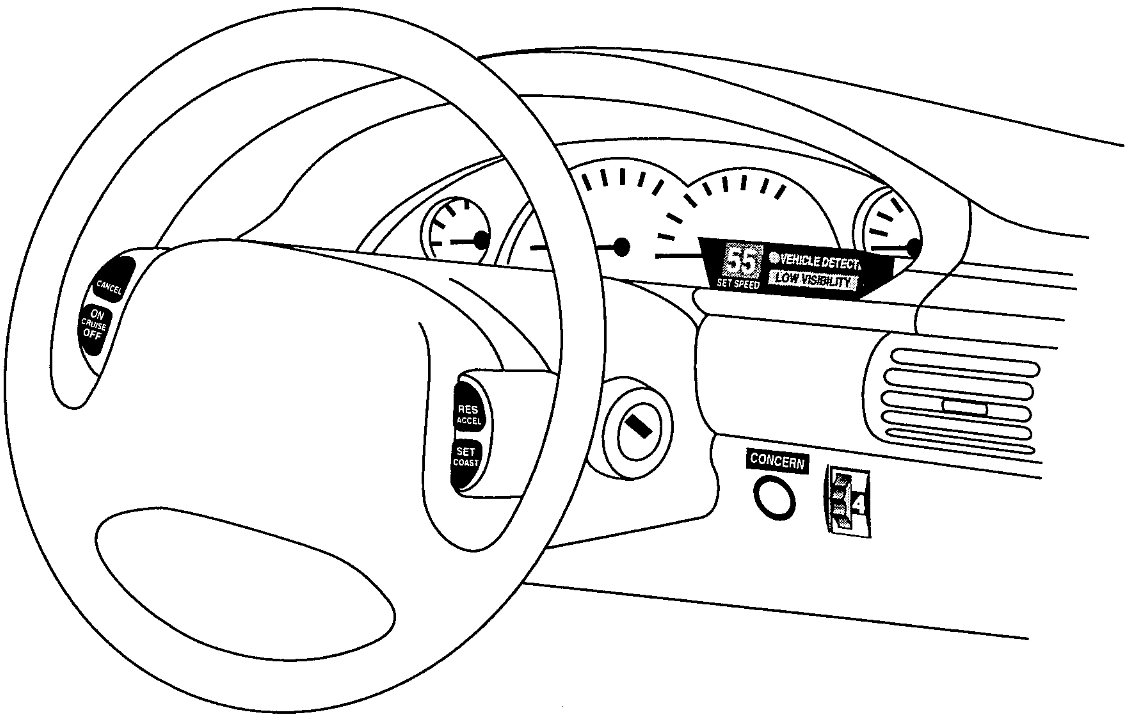

Figure 13. Chrysler Concorde instrument panel with ACC controls and displays

The ACC driver interface includes a display for presenting the set speed to the driver, a light accompanied by an audible tone for indicating when the sensor's performance is inhibited by visibility, and a light for indicating when the ACC system has recognized a preceding vehicle. In addition there is a *thumb-wheel* switch for the driver to use in selecting headway time (shown with a selected setting of 4, to the right of the concern button in Figure 13). Headway adjustment (i.e., the value of Th) was referenced on the thumb-wheel switch by an indication value from 1 to 8. The lowest setting (No. 1) corresponded to a headway time of 0.6 seconds and the highest setting (No. 8) corresponded to 2.0 seconds, with 0.2 second increments for each digit in between.

3.0 Test Results and Experience Gained

Operating experience was gained during the past year by the UMTRI researchers who were driving the vehicle. The new ACC vehicle was driven and evaluated by fourteen researchers whose familiarity with ACC systems ranged from basic to very experienced. This section presents results that are based upon the judgments of those drivers.

The initial usage of the ACC-with-braking system by UMTRI's professional staff has produced recorded data and field notes covering a broad range of system configurations, parameter settings, and operating conditions. These data are being processed and evaluated. Preliminary results are presented here.

3.1 Driving Situations

A prescribed set of five driving situations was established to ensure that (1) each test driver was exposed to a similar set of operating conditions, and (2) the scope of the system's performance range would be explored in an efficient way. Each of the participating drivers was given a list of the driving situations and was asked to drive at least long enough to experience these situations and to be able to answer questions regarding them.

Since testing was conducted on public roads, it was feasible to cover a broad set of operating scenarios in a relatively short driving trip. Each of five prescribed driving situations was selected to elicit a certain response that would serve as a meaningful exercise of the system. During these tests, data were collected using the instrumentation package described earlier.

The approach employed for determining the driving situations was based upon identifying generic, fundamental tasks that the system may be expected to perform. The drivers were requested to exercise the ACC system and then answer questions regarding the following situations:

- *Closing-in on a preceding vehicle*

  This test examines the ACC transition from the speed-control mode to the headway-control mode. Until the time the preceding vehicle is first detected, the ACC vehicle uses the V_{set} value to determine its speed. As the ACC system proceeds to slow the vehicle, however, it attempts to match the speed of the preceding vehicle and to maintain a distance corresponding to the preselected headway time.

2. *Following a vehicle*
   The purpose of this test is to see how well the ACC system maintains headway during nominally steady following situations. The drivers were also instructed to change headway setting while following, in order to observe the ACC transient response to an abrupt change in headway setting.
3. *Passing*
   Conceptually, the passing test can be thought of as the converse of the closing sequence. This test starts with the ACC vehicle following a preceding vehicle at some speed which is lower than V_{set}. When pulling out into the adjacent, clear lane, the ACC system automatically accelerates the vehicle back to V_{set}. This sequence allows the driver to evaluate the ensuing rate of acceleration.
4. *Cut-in*
   In the cut-in test a preceding vehicle appears suddenly and at a short range in front of the ACC car. The purpose of this test is to evaluate the responsiveness of the system to a newly acquired conflicting target and to explore ACC performance under situations that are closer to crash avoidance.
5. *Buzzer activation*
   Drivers were requested to provide observations regarding the warning that was incorporated into the ACC system. Recognizing that the buzzer could activate in almost any of the above four scenarios, drivers were asked to comment on any of the situational cases in which it triggered.

Although this set of situations does not cover all aspects of ACC driving, it does provide a good sampling under which drivers can evaluate the performance of the system. The set of five cases does allow the researcher to gain useful feedback and to utilize this pilot-testing process to verify proper functionality of the system.

3.2 Subjective Results

Each of the participating drivers was given a debriefing sheet that included specific questions regarding the five driving situations. Appropriate space was also provided in this questionnaire for free-form comments or observations regarding the system's overall functionality.

The results of the questionnaire are reported here in the form of histograms. Each question addressed a specific performance feature of the system, for which the possible responses were excellent, good, ok, marginal, or bad. The horizontal axis in the following histograms lists the *bins* corresponding to each of the possible responses, and the column height represents the count of answers in each bin.

1. *Closing-in on a preceding vehicle*

   The first question addressed the range at which the system initiates its response during closing. (see the discussion regarding the parameter, Δ, and the top horizontal line in Figure 9.) Figure 14 shows that most drivers judged the Δ range setting to be good.

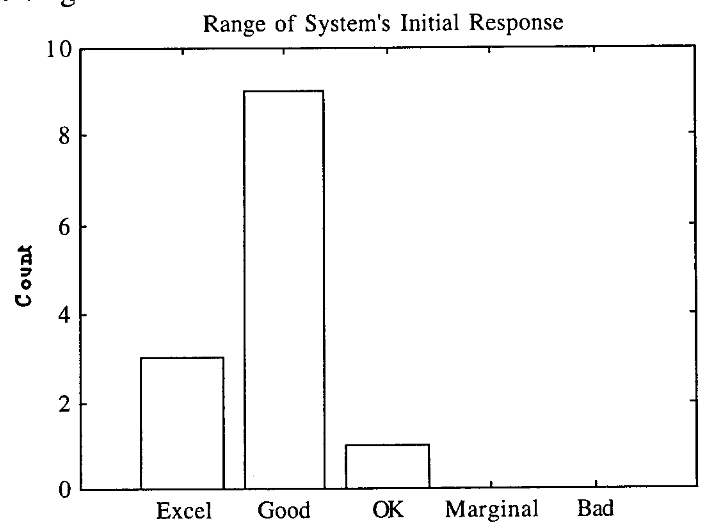

Figure 14. Range of system's initial response

Once the system engages a preceding vehicle during closing, it starts to decelerate. The rate of deceleration depends on the initial speed difference between the two vehicles and on the range at which ACC headway-control response was initiated. A second question addressed the appropriateness of this deceleration rate. Shown in Figure 15 are results indicating that this system property was also reasonably satisfactory for most of the test drivers.

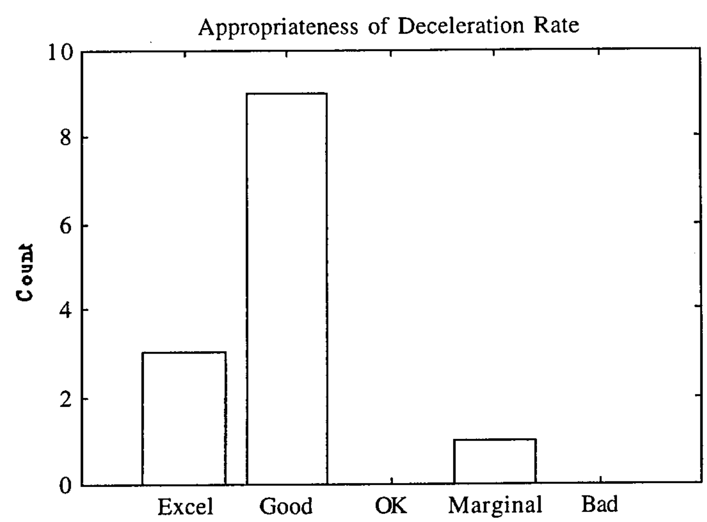

Figure 15. Appropriateness of deceleration rate

Figure 16 presents a relatively approving set of responses to a question concerning the driver's awareness of the system's actions. Similarly, another question sought opinions, as shown in Figure 17, about the smoothness of the closing-in process. In trading off these two features, there is a potential for intrinsic design conflict since smooth deceleration may tend to delay the driver's awareness of the system's response. The results in Figure 17 may indicate that the degree of jerk allowed during closing was somewhat higher than desired.

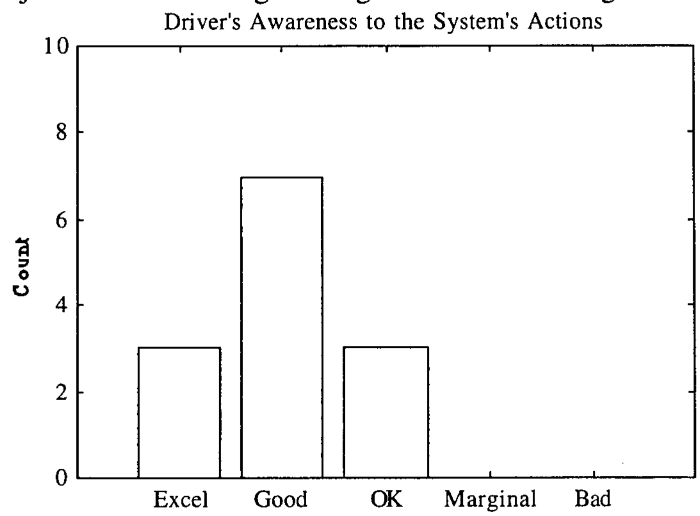

Figure 16. Driver's awareness to the system's actions

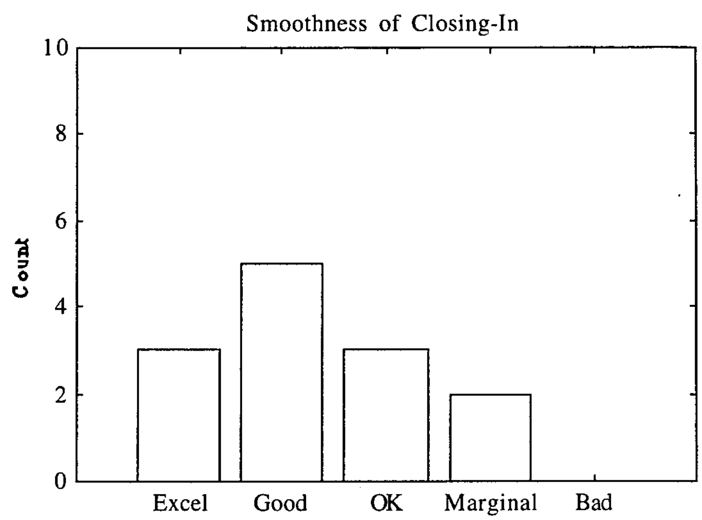

Figure 17. Smoothness of closing-in

2. *Following a vehicle*

Five questions addressed the situation of steady following behind a vehicle. Note that drivers were also asked to exercise a change in their headway setting at some time during steady following. A one-step change in the thumb-wheel setting would introduce a 0.2 second increment in the desired value of headway time. The answers for the first question – "How appropriate was the selection range of headway settings?" – are summarized in Figure 18. It appears that the provided range of headway settings serves its purpose well.

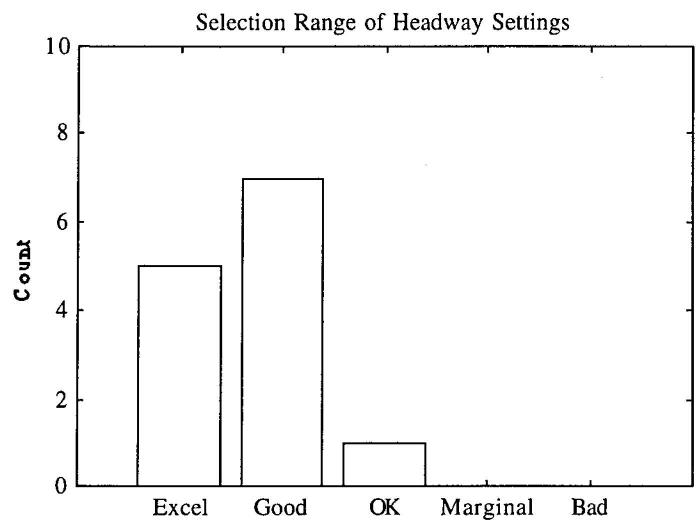

Figure 18. Selection range of headway settings

Shown in Figure 19 are comparable responses to a second question which addressed the degree of smoothness perceived while engaged in steady following.

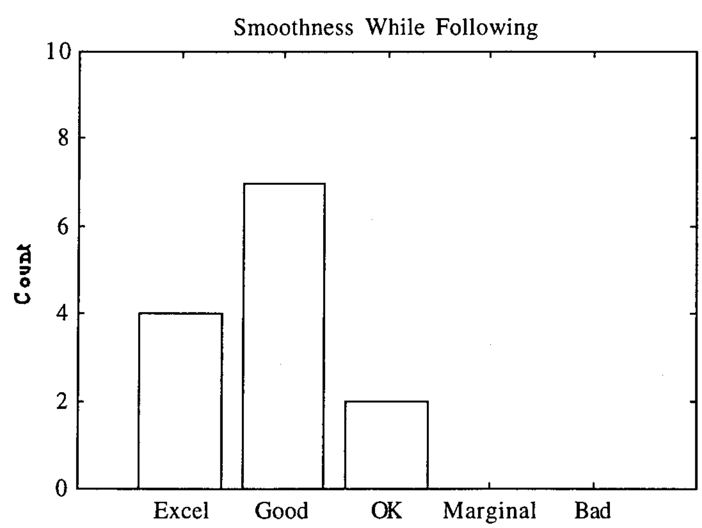

Figure 19. Smoothness while following

A third question evaluated the System's ability to maintain the selected headway. This quality of the system also tends to be in conflict with a "smoothness" attribute. That is, the smoother the headway-keeping response, the less likely the system will tightly control to minimize headway error. The results in Figure 20 suggests that the system's ability to keep headway has suffered in favor of the smoothness attribute.

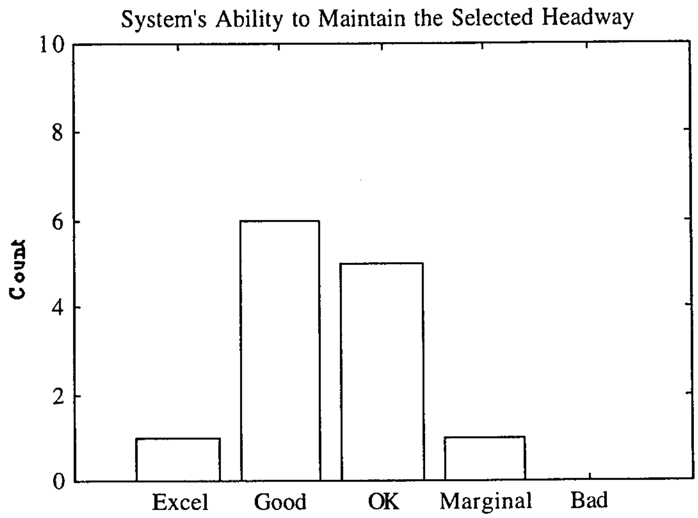

Figure 20. System's ability to maintain the selected headway

Next, the drivers were asked about the system's response to (a) changing to a longer headway while following and (b) changing to a shorter headway. As shown in Figure 21 and Figure 22, most drivers felt that the system performed well when transitioning to either longer or shorter headway values. Responses were, however, more negative when addressing the short-headway transition. This trend was consistent with the sluggish acceleration of the vehicle which is discussed in section 2.6. That is, drivers were unhappy with the long time it took for the vehicle to "catch-up" to the shorter headway.

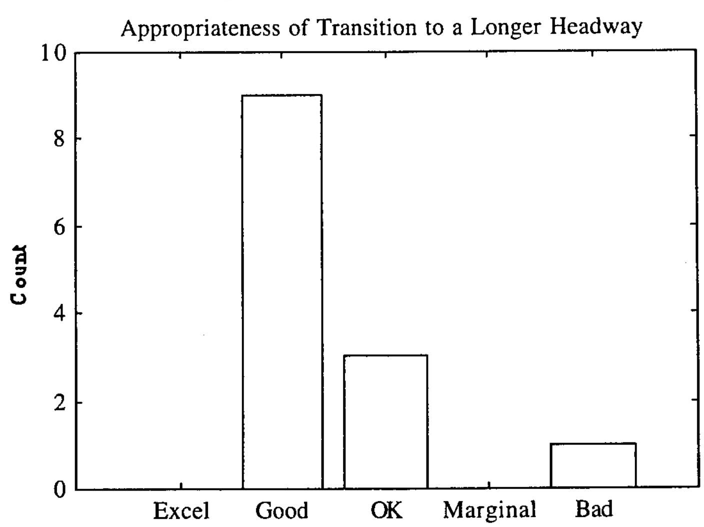

Figure 21. Appropriateness of transition to a longer headway

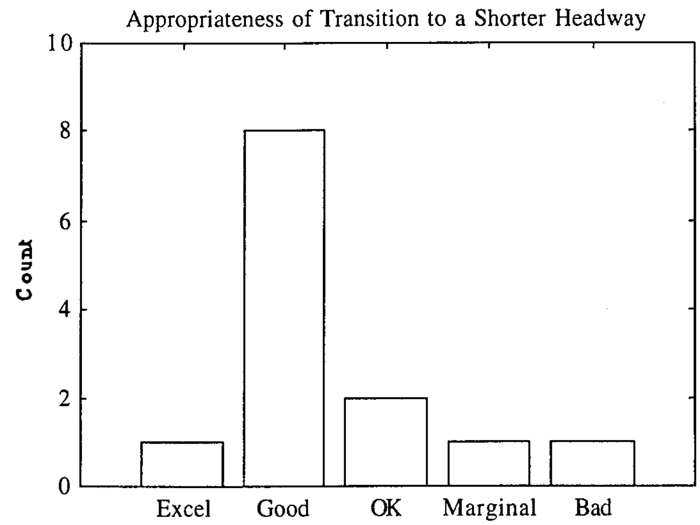

Figure 22. Appropriateness of transition to a shorter headway

3. *Passing*

The questions that pertained to the passing situation drew the most negative responses. In the first two questions, drivers were asked to evaluate the smoothness of the acceleration and the appropriateness of the rate of acceleration, respectively (see Figure 23 and Figure 24). Responses to the second question were quite predictable. That is, the sluggish acceleration obtained while recovering velocity to the set-speed level was highly criticized. The spread of responses to the first question, however, was rather surprising, since the very gradual nature of the throttle application causes the ensuing acceleration to be remarkably smooth. It may be that those who rated the smoothness as "marginal" or "bad," confused the smoothness issue with that of appropriateness, in this question.

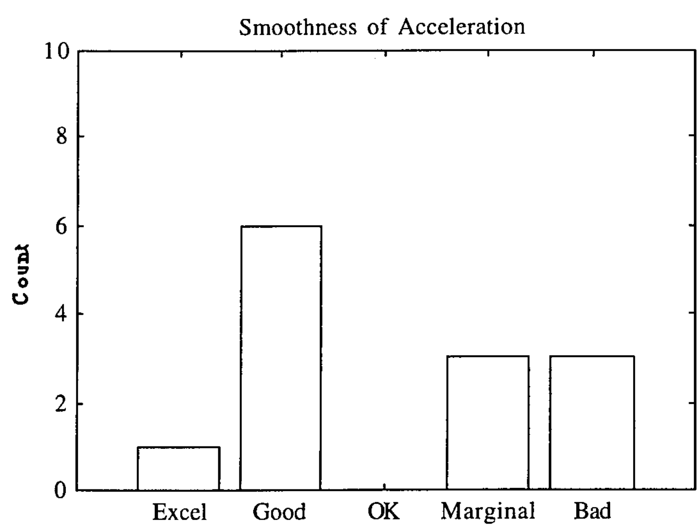

Figure 23. Smoothness of acceleration

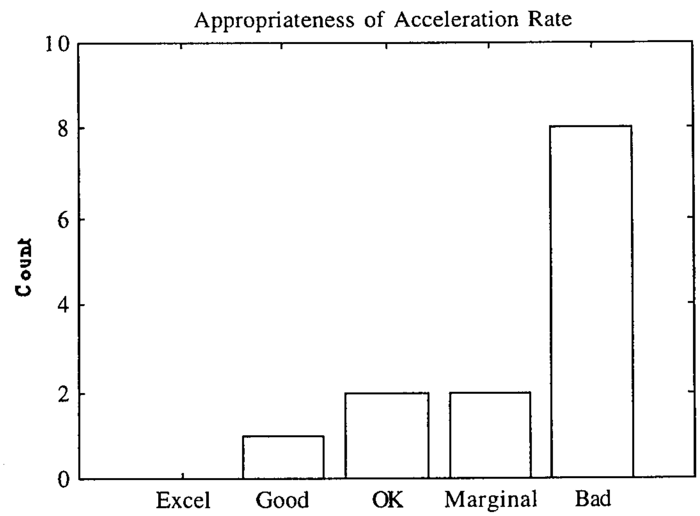

Figure 24. Appropriateness of acceleration rate

When asked to evaluate how clearly the system's actions were perceived during passing, most drivers responded with "good" or "ok," although some rated this feature as "marginal." Though sluggish and slow, it appears that the acceleration rate was noticeable.

4. *Cut-in*

Although drivers were asked to evaluate the system's response to cut-in events that occurred spontaneously, they also could instigate the situation by themselves cutting behind a slower-moving vehicle in the adjacent lane.

Most of the participants thought the system's response to cut-in was timely, as noted in Figure 25. It should also be pointed out that some drivers drove with mis-aligned sensors which caused delays in detection (other comments regarding the alignment issue are presented at the end of this section).

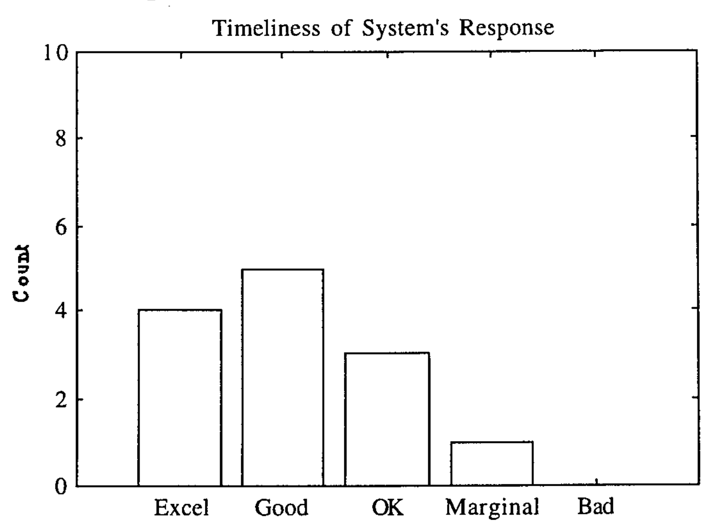

Figure 25. Timeliness of system's response

The deceleration rate that prevailed in response to the cut-in form of conflict was also considered appropriate by most drivers, as shown in Figure 26. Again, late detection in certain cases due to sensor misalignment may be responsible for some of the lower rankings.

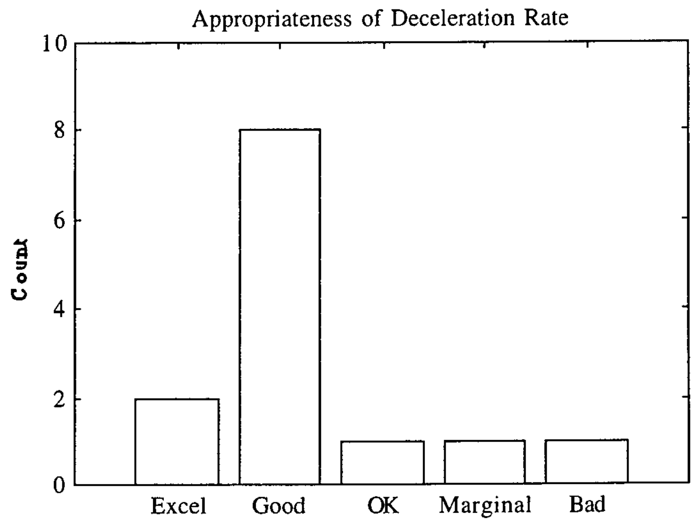

Figure 26. Appropriateness of deceleration rate

As shown in Figure 27, drivers reported only moderate confirmation of their awareness of the system's actions during cut-in. Most of them, however, thought that the action was clear enough.

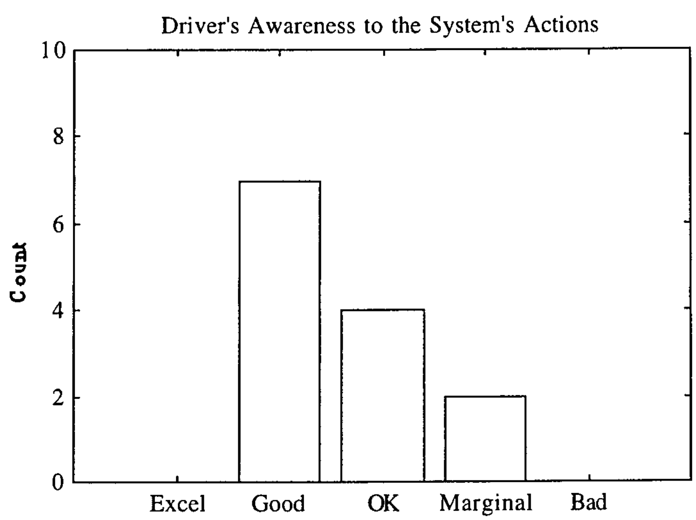

Figure 27. Driver's awareness to the system's actions

5. *Buzzer activation*

Buzzer-related questions provided the most diverse responses. Although the warning device was criticized, none of the responses considered any of the buzzer's aspects to be simply "bad." In general, the responses to the timeliness question, in Figure 28, correlated with the responses to the buzzer's perceived contribution to safety, in Figure 29. Drivers who found the buzzer timely, also considered it as contributing to safety. Similarly, drivers who thought that the buzzer's timing was inappropriate (i.e., it came on too soon), were eventually annoyed by it and felt that it would not contribute to safety.

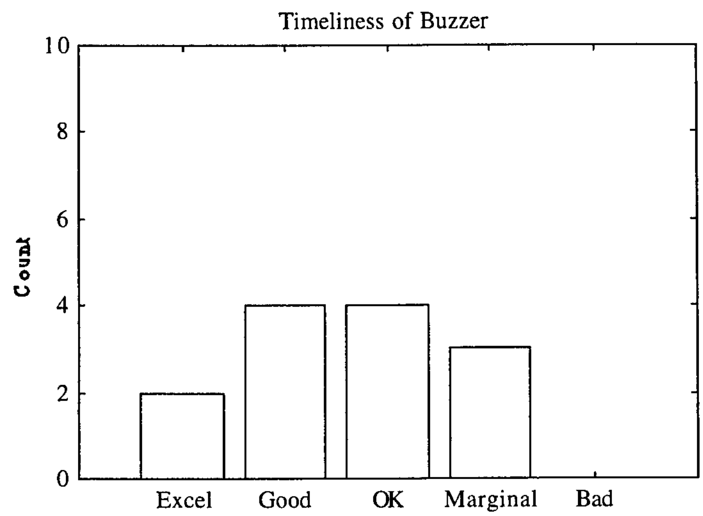

Figure 28. Timeliness of buzzer

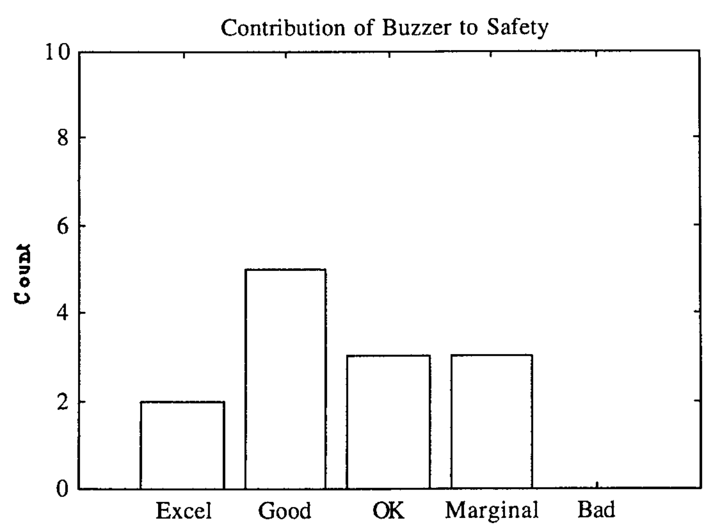

Figure 29. Contribution of buzzer to safety

The questionnaire provided for additional, free-form comments which were not guided by specific questions. Drivers contributed the following responses to various functional aspects of the ACC-with-brakes system:

☆ *Comments about the system's performance in general*

- Overall the system works well. (4 comments)
- The nonbraking behavior improved remarkably compared to the FOT system.
- The resume function of the cruise control failed occasionally. (3 comments) {**Note**: an error was found in the algorithm code and it was fixed.}
- Concern with fuel waste and poor mileage due to a too-frequent use of the brakes.
- Concern with the system's performance in hilly areas (comment about Michigan being flat).
- Experienced an unexplained disengagement; it went unnoticed until closing on a car with no response.

☆ *Comments relating to sensors*

- Too many false targets, especially with trucks in the adjacent lane and no car ahead in my lane; sometimes had to accelerate manually to pass. (6 comments) {**Note**: the sensors were misaligned; realigning the sensors seemed to solve the problem.}
- Hesitation when acquiring a truck with a flat-bed trailer.

☆ *Comments about algorithm design*

- When increasing T_h, the brakes came on sometimes; suggest using coastdown as the only means of deceleration when possible: if $R < R_d$ but $R_{dot} \geq 0$ use coastdown only, unless very close.
- Would prefer the system's initial response to be sooner and at a longer range (while closing).
- It appears that the system is tuned to accommodate "flying passes;" response during closing might be too late for "gliders."
- Very timely throttle response during a cut-in; could feel the start of coastdown.
- System should use brakes to control speed on downgrades even without a target.
- Need a delay on cut-in, system "thought" $R_{dot} < 0$ where, in reality, $R_{dot} > 0$.
- Increase T_h and make the "aggressiveness" of the system a function of the T_h setting.

- At short Th: brake function is OK, make the throttle much more responsive; at long Th: throttle function is OK, minimize use of brakes.

☆ *Comments about oscillations and smoothness*

- Sometimes felt a rough pulsing action while closing. (2 comments)
- Oscillations due to undershoot when closing from a distance while on an upgrade.
- At Th below 1.0 second, system's delays cause oscillations in following mode (close throttle – brake – apply throttle, close throttle – brake – apply throttle, etc.).
  {**Note**: a known issue due to delays; drivers were discouraged from using Th<1.0}.
- Smoothness of following was not as good as expected — it appears to oscillate.
- Problem with the "accel side" of the following cycle.
- At close range the system seemed to be "hunting" before settling on a range.
- At 1second headway, cutting behind a slower vehicle, decel application was unsmooth in 3-4 steps.
- At Rdot of about 15 mph, transition was smooth.

☆ *Comments about acceleration*

- Acceleration rate insufficient when pulling to pass, causes an impediment to traffic; Inadequate resume rate is the system's weakness. (**9 comments**)
- Overtaking is improved compared to the FOT system.
- Felt that when pulling to a free lane, the system's initial response was to drop the throttle; very awkward.
  {**Note**: the code was reviewed; probably pulled out just when coasting started.}

☆ *Comments about brake application*

- Did not feel the brakes were ever applied too soon. (6 comments)
- Felt that braking sometimes was too late. At one time, the warning came on when it seemed that more braking would have resolved the conflict. (3 comments)
- Braking was good, but it took the car too long to get back and follow again.
- Braking felt too much and too long when closing behind a vehicle that was braking also (caused recovery to feel very delayed).
- Did not feel the brakes were applied too little or too late; an OK "hunter-glider" balance. (5 comments)

- Would like to get more decel.
- Brakes delayed coming on during a cut-in — had to intervene to avoid accident.
- One time, on a two-lane road, the brakes didn't seem to work at all.
- Braking transition felt too steep; perhaps start braking at a lower threshold to reduce the rate of change of pressure. Perhaps braking was too much too late.

☆ *Comments about the buzzer*

- Buzzer is annoying and sounds too often; due to different decel levels at different speeds, buzzer sounds more often at 40 to 50 mph than it does above 55 mph.
- Did not like the buzzer at all; would prefer a system with no sound.
- Buzzer went off too often for close cut-in.
- Was surprised at how often the buzzer went off, but with an "accommodating" approach; about 50% of the warnings were appropriate.
- Surprisingly liked the buzzer; had an occurrence of the buzzer going off when overriding to pass while getting too close. Liked its collision avoidance function.
- Need to implement a buzzer.
- Implement a two-tone design for the buzzer activation.

3.3 Design Issues

Overall, the responses from the drivers who participated in the pilot test indicated that the design approach used in the ACC test vehicle was appropriate. With the exception of comments that address errors and misalignments (which were duly corrected), or deficiencies of the system over which we have no control (such as the OEM engine controller), all other comments pertain to adjustable parameters.

Adjustable parameters are values used by the algorithm that can be changed on-the-fly. That is, they can be modified while the vehicle is in motion, without a need to stop or reprogram the controller. By doing so, researchers can obtain immediate feedback on how different parameter values affect the system's performance. Other operational settings (such as the coastdown deceleration of 0.04 g) can only be changed in the algorithm code and will necessitate recompiling of the program and downloading it into the car. The parameters that were incorporated into the system's design allow for a temporary modification of the settings; once the system is turned off, the modified values are erased and the default values are restored when the system is turned on again.

Findings from the preliminary tests, as they affect the system's design, are presented here by the characteristics which they influence:

- Deceleration authority — The maximum deceleration level of 0.22 g can handle almost all headway conflicts encountered during normal highway driving. The results of the pilot test did not indicate that the broad cross-section of drivers would prefer more deceleration.
- Jerk level — The jerk level (the rate of brake-pressure application) is an adjustable parameter. Prior to the pilot testing, experiments were conducted with various jerk-level limits. During the pilot tests, however, jerk was limited only by the built-in ramping feature of the smart booster (about 0.6 g/sec). From the test-driver responses, this level seemed to be satisfactory most of the time, although some drivers commented that the rate might be too steep and that perhaps it would be desirable to have the rate situation-dependent.
- Warning — The warning feature should be explored further. In the work reported here, the threshold was fixed. Driver responses suggest that various levels and thresholds should be investigated in the future.
- Display — No questions were addressed specifically to issues involving the driver's display and MMI (Man-Machine Interface). Since no input regarding the MMI was provided under "other comments concerning the ACC system," the design is assumed to be adequate. Nevertheless, since the display is based on that of the FOT and some drivers in the FOT study commented that the display was lacking, some further improvement may be in order.
- Headway time range — Given the current acceleration limits, the system does not function well enough at T_h values that are below 1.0 seconds. It might be desirable, therefore, to change the headway values assigned to the different settings of the thumb-wheel so as to allow T_h values only between 1.0 and 2.0 seconds.
- Acceleration — The sluggish acceleration has been criticized by nearly every driver. Work needs to be done with Chrysler to resolve the issue.
- Speed boundaries — Current speed boundaries (whose minimum values are 30 mph to set and 25 mph to resume and whose maximum set value is 85 mph) are determined by the OEM cruise control. These limits seem appropriate for this type of ACC operation. Until the project gets further into crash avoidance or the stop-and-go application, there is no plan for changing these values.
- False deceleration — The system in general and the smart booster in particular have proven themselves quite unsusceptible to unexplained false deceleration. In those incidents that false deceleration did take place, it was (1) because of sensor

misalignment, and (2) of no dramatic nature. Aligning the sensors and limiting their field of view seemed to eliminate the problem.

- Vigilance and inattentiveness — Experiments have not been run with sufficiently long driving exposure to be able to evaluate the extent to which the driver's reliance on the system will make him/her inattentive to the forward scene. Another driver-supervision-related question is the driver's vigilance and ability to identify arrival at the deceleration limit so as to manually take control of the brakes. Assuming that the driver is attentive to the forward scene, two observations were made regarding this limit, namely, (1) a system deceleration limit of 0.22 g will take care of a very high percentage of the headway conflicts encountered on the highways, and (2) even when a 0.22 g-conflict presents itself, drivers are seen to be instinctively quick to intervene. That is, limited evidence suggests that drivers do not "wait and see" if the system can handle the conflict. Also the *learning curve* is quite steep, and the UMTRI drivers became familiar with the system's performance limits rather quickly. Nevertheless, these issues need to be investigated further.

4.0 Summary of Findings

4.1 Analysis of the Results

The subjective results presented in section 3.2 clearly indicate that the acceleration level used in increasing the speed of the ACC vehicle was not satisfactory in the opinion of most of the test drivers. Their evaluation was overwhelmingly negative with 8 ratings as bad, 2 as marginal, 2 as OK, 1 as good, and 0 as excellent. This set of ratings is the only set predominated by the bad rating.

In their comments, nine test drivers indicated that the resume rate of the system was the system's weakness. It appears that other comments about when and how much to decelerate may have been influenced by the vehicle's slow response to a command to accelerate. The drivers did not want to slowdown too much because they were concerned with how long it would take to get back up to the desired speed and headway time gap. The drivers' comments and the ratings show that something should be done to increase the acceleration used in closing a time/distance gap created by slowing down. (Specific recommendations concerning this and other matters are presented subsequently in section 4.2.)

There were no bad ratings concerning the buzzer that was used to warn the driver when the system was asking for the maximum deceleration authority allowed by the system. The ratings were fairly uniformly spread from excellent to marginal. The expert test drivers were not of a common mind with regard to their evaluation of the buzzer. It should be noted that these drivers are referred to here as expert drivers as a means for distinguishing them from lay drivers. Most of them do not possess any high level of expertise with ACC systems, however, the fact that they were involved in one way or another in the ACC field operational test, prohibits us from considering them as volunteer, lay drivers such as the participants in the FOT. Judging from their comments, it appears that there are some drivers who do not like buzzers in general and some drivers who thought the features of this buzzer could be improved. Other drivers found the buzzer to be fine. These results do not resolve the issue of intervention prompt, or warning, in any definitive way.

The ratings concerning the deceleration level, the following control, and the system's smoothness were quite good. This overview statement is supported by observing that if the accelerating and buzzer issues are neglected, the other issues combined together yield

87 good ratings and 29 reports of excellent as compared to 9 ratings of marginal and 3 reports of bad.

However, an examination of the comments other than those related to accelerating and buzzer issues yields indications that certain features of the system may yet warrant improvement. This examination entails looking at the comments concerning algorithm design, oscillations and smoothness, and brake application while presuming that acceleration-related concerns will be resolved.

The oscillations and smoothness comments turn out to be related to algorithm design in that the concept for following, as implemented in the algorithm, contributes to the oscillations observed by the drivers. Qualitative thinking indicates that these concerns could be resolved by eliminating the special following region (the shaded region in Figure 9) and by using the velocity-command rule originally used in the FOCAS project with the SAAB 9000 vehicle. The SAAB had plenty of acceleration capability. In fact, a velocity-rate limit was added to the SAAB to keep it from accelerating so fast that the drivers complained. In addition, the ACC controller in the SAAB did not exhibit the oscillation problems observed here, nor did the Chrysler vehicles used in the ACC FOT. This means that working with the basic-objective line shown in Figure 9, but not employing the following-objective line, also shown in Figure 9, would be expected to reduce or eliminate the oscillatory tendencies observed in this test exercise even if a change in the Chrysler cruise control function causes the low acceleration capability to be resolved.

Examination of the comments with regard to brake application does not clearly indicate an overwhelming need for changing the automatic-brake-control provisions. On the other hand, there were a number of comments that appear to indicate that brake application is delayed relative to the driver's preferences. This suggests that the braking rules need further scrutiny. It appears that the rationale for locating the a_{Bmin} and a_{Bmax} lines (shown in Figure 9) needs to be reconsidered or possibly a different braking philosophy might need to be developed. Recommendations for various braking possibilities are presented in the next section.

4.2 Recommendations

The following recommendations pertain primarily to matters associated with structuring the design of the ACC system to be used in testing exercises planned for the spring of 1998. In general, these design recommendations address two topics: (1) rules, plans, and procedures for modulating the throttle to control headway, and (2) rules, plans, and procedures for applying braking to extend the functionality of the ACC system beyond that achievable with throttle modulation alone.

4.2.1 Modulating the Throttle

There is a pressing need to improve the acceleration performance obtained through the use of the conventional cruise control system installed in the Chrysler Concorde. Informal discussions with Chrysler engineers led UMTRI to conclude that the route of modifying the software in the engine controller would not be feasible. Rather, it is recommended that the operation of the "accel" button of the cruise control be emulated in a manner that will cause the vehicle to accelerate more rapidly when increases in speed greater than approximately 4 mph are commanded by the commander unit of the ACC system.

In conjunction with this, it is recommended that the rules for generating the velocity commands that are used for modulating the throttle be simplified to be more like those used in the original FOCAS vehicle (the SAAB 9000) and in the Chrysler Concordes used in the ACC FOT. Specifically, this means incorporating the following generalized functions into the section of the commander dealing with throttle modulation:

1. Initiate headway control (*headmode*) upon entering the shaded region shown in Figure 30. The "script" describing the rules for initiating and terminating headway control is as follows:
    - Initiate headmode if ($R < Rmax$) and ($R < R_h + k_3$ Rdot) and ($Rdot < 0$).
    - Terminate headmode if ($Vc \geq Vset$).
    - Once headmode is initiated, it stays true until it is terminated.

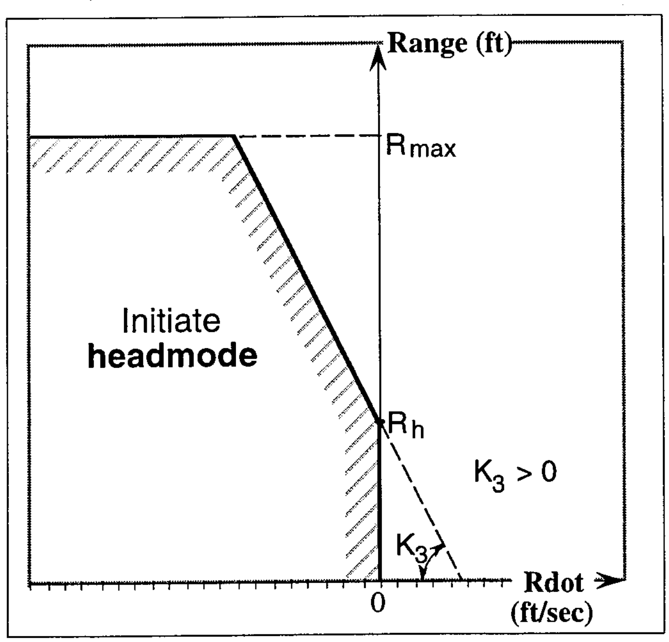

Figure 30. Initiating headmode

2. When headmode is true, perform the ACC functionality using the following equation to determine commanded speed:

   $$Vc = V + Rdot + (R - R_h) / (K_3) \tag{7}$$

This command is then presented to the engine controller to adjust the throttle in order to attain the value, Vc. There is no need to stipulate a limit on the acceleration level such as was employed with the SAAB because the Chrysler cruise control seems to have a rate limit that is more than adequate to provide a smooth ride.

Equation (7) applies for both positive and negative values of Rdot. When the velocity command results in zero throttle (closed throttle), the system simply coasts, losing speed due to tire rolling resistance, aerodynamic drag, engine and transmission drag and other sources of natural retardation. These inherent properties of throttle operation mean that the maximum deceleration during throttle modulation is equal to the coast down deceleration of the vehicle. The coast down deceleration alone is enough to perform the ACC functions of closing and following in most circumstances.

When the brakes are used to achieve a deceleration level above that of coasting, the throttle is expected to be closed at zero throttle.

4.2.2 Applying the Brakes

The following discussion pertains to the application of the brakes in extending the functionality of the ACC system.

When in headmode, the brakes may be applied to reduce speed. The conditions describing when and how much braking is allowed are described by the following script.

1. Braking is permitted when all of the following conditions are satisfied:
   - $Rdot < 0$, and
   - $R < k_2 R_h + Rdot^2 / 2 a_{Bmin}$, and
   - $R < k_6 R_h + Rdot^2 / 2 a_{Bcoast}$

   The region where braking is permitted is illustrated in Figure 31.

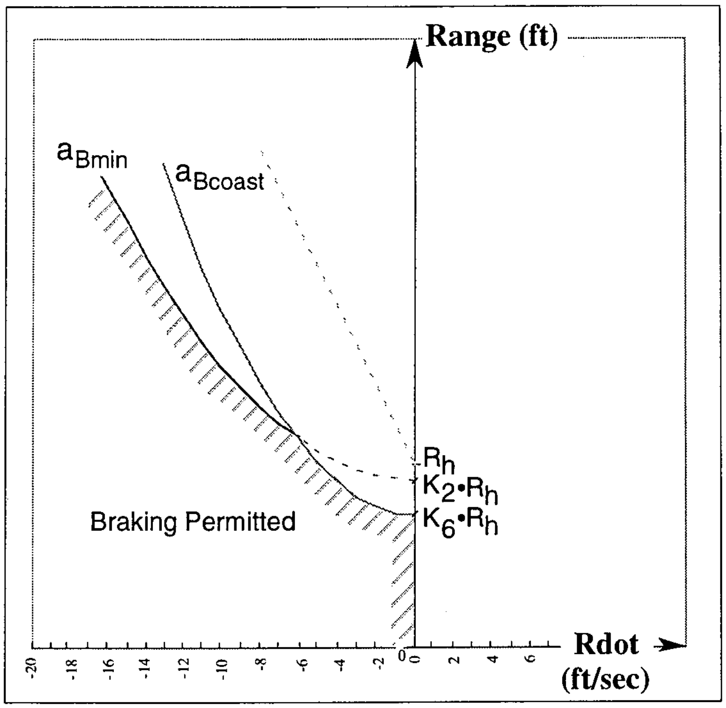

Figure 31. Braking region

2. The level of braking depends upon R, Rdot, and R_h. The maximum level of braking depends upon the control authority (a_{Bmax}) chosen for the system. The boundary where a_{Bmax} starts is shown in Figure 32. The equation for this boundary is as follows:

$$R = k_5 R_h + Rdot^2 / 2\, a_{Bmax} \tag{8}$$

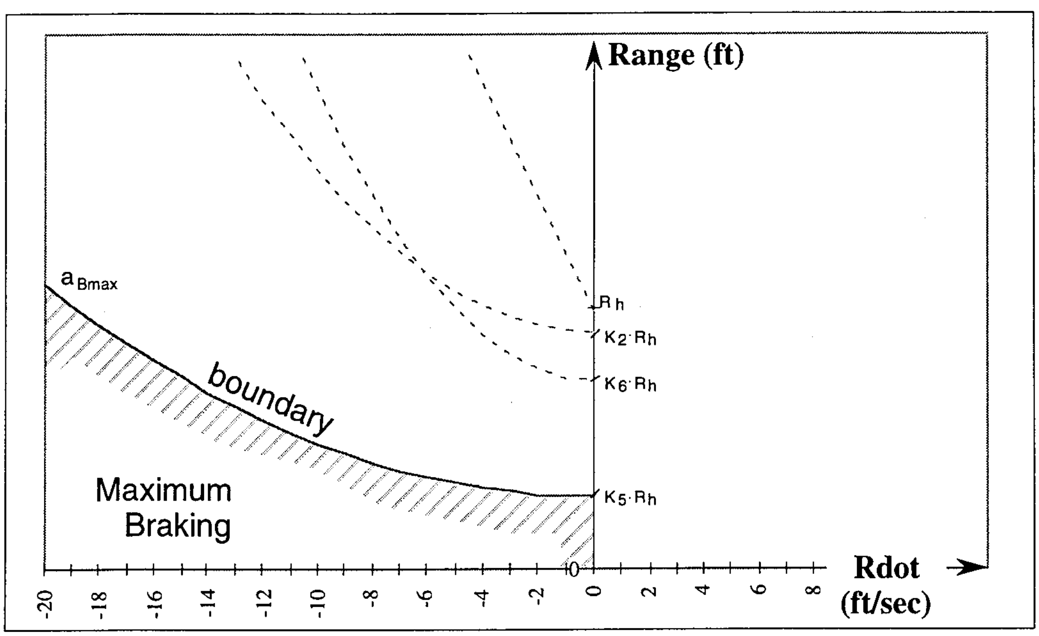

Figure 32. Maximum braking boundary

Below this boundary, maximum braking is applied. Above this boundary and within the braking region, the level of braking is determined by interpolation rules or other special rules. The form of these rules needs to be decided before the field tests start. There are three possibilities that are worthy of consideration:

First Possibility Use the values of R and Rdot to find an intercept for the deceleration parabola to be used in solving for the deceleration command, a_c. The following equations can be used to find a_c:

$$R_{top} = K_2 R_h + Rdot^2 / 2 a_{Bmin} \quad (9)$$

for Rdot less than the value of Rdot where the a_{Bcoast} and the a_{Bmin} parabolas intersect in the braking region. For Rdot ≥ the intersection value,

$$R_{top} = K_6 R_h + Rdot^2 / 2 a_{Bcoast} \quad (10)$$

$$R_{bot} = K_5 R_h + Rdot^2 / 2 a_{Bmax} \quad (11)$$

Interpolating for an intercept,

$$R_a = [((R - R_{bot}) / (R_{top} - R_{bot})) (K_2 - K_5 \text{ or } K_6 - K_5) R_h] + K_5 R_h \quad (12)$$

Finally,

$$a_c = [Rdot^2 / 2 (R - R_a)] \quad (13)$$

Second Possibility This possibility is similar to the first possibility, except that it uses a different interpolation scheme which results in the following equations:

$$a_c = (2 R_h s + Rdot^2) / 2(R - K_0 R_h) \quad (14)$$

where the coefficients K_0 and s are computed using the following equations:

$$s = (K_2 - K_5 \text{ or } K_6 - K_5) a_{Bmax} \; a_{Bmin} / (a_{Bmax} - a_{Bmin}) \quad (15)$$

$$K_0 = K_5 - (s / a_{Bmax}) \quad (16)$$

Third Possibility This possibility uses the deceleration to barely avoid a crash, a_{crash}, and an "anxiety" function to increase the deceleration as R gets small. In this case, the following equations can be used to find a_c:

$$a_{crash} = Rdot^2 / 2 R \quad (17)$$

A proposed form for the anxiety function is as follows:

$$A = (k R_h / R)^n \quad (18)$$

which means that high anxiety occurs at short range.

Finally,

$$a_c = A \, a_{crash} \quad (19)$$

4.2.3 Summary of system recommendations

In summary, it is recommended that a simple rule for modulating the throttle should be used to achieve the basic ACC functionality. See 4.2.1 for more detail. Braking should be used to adjust vehicle deceleration in a manner that will lead to headway time and distance gaps such that throttle modulation can control headway. Braking should be applied in a progressively increasing manner as R gets smaller and Rdot gets more negative (more negative indicating more rapidly closing on an impeding vehicle). See 4.2.2 for more detail. In addition to those items specified in 4.2.1 and 4.2.2, it is recommended that the minimum desired headway time gap Thmin should be set at 1.0 seconds and the maximum value of Th (Thmax) should be approximately 2 seconds. Every effort should be made to improve the forward-acceleration capability of this vehicle when it is under ACC control. Even though the driver can always override the system and accelerate at a level exceeding that achieved through ACC control, experience shows that drivers do not readily override the system and drivers are slow to learn to apply the accelerator pedal when operating with ACC. Nevertheless, a satisfactory amount of forward acceleration is needed for the driver to feel that use of the ACC system is comfortable and convenient. Finally, with regard to the buzzer issue, it is recommended that the warning system should have a nonaggressive signal (a friendly "beep beep" seems preferable) to inform the driver when braking at the full deceleration authority of the ACC system has been reached. Further consideration should be given to adding another, more aggressive, signal to warn when the deceleration needed to barely avoid a crash exceeds the control authority of the ACC system.

5.0 Plans and Expectations for Next Year

5.1 Testing With Lay Drivers

During the next year, we plan to conduct two test exercises involving lay drivers. As shown in Figure 33, these exercises are scheduled to start in April and September 1998. The first testing activity will be on a proving grounds using confederate vehicles to mimic driving situations pertinent to ACC driving. Given that the first set of tests is expected to show that the system is roadworthy, the plan for the second round of testing involves lay drivers operating on the highway. Techniques similar to those employed in the first year of this FOCAS project will be used [1].

The proving grounds tests will involve the ITT/ADC test vehicle with the UMTRI system for generating velocity and deceleration commands. This means that we will be able to set key parameters in the commander algorithms so as to represent different versions of ACC control.

Our preliminary ideas for proving ground testing involve the use of procedures that will employ either conventional cruise control or the ACC system. It is envisioned that testing will focus on two fundamental conflict situations that call for active management of headway. These situations are closing from long range and impeding vehicle deceleration.

The testing process is expected to be performed in two stages. In the first stage, the driver will simply operate the following vehicle under conventional cruise control. During this stage, the objective is to characterize certain driver properties that, hopefully, capture an estimate of this subject's own headway-management behavior (although the driver will be intervening upon the conventional cruise mode in manifesting this behavior). In the second stage, the ACC system will be engaged using two sets of parametric values. One set of values will be based on results of the driver characterization that was performed moments before, and the other will be a standard set used for reference purposes. Both subjective and objective data will be gathered to document driving experience in the second stage testing.

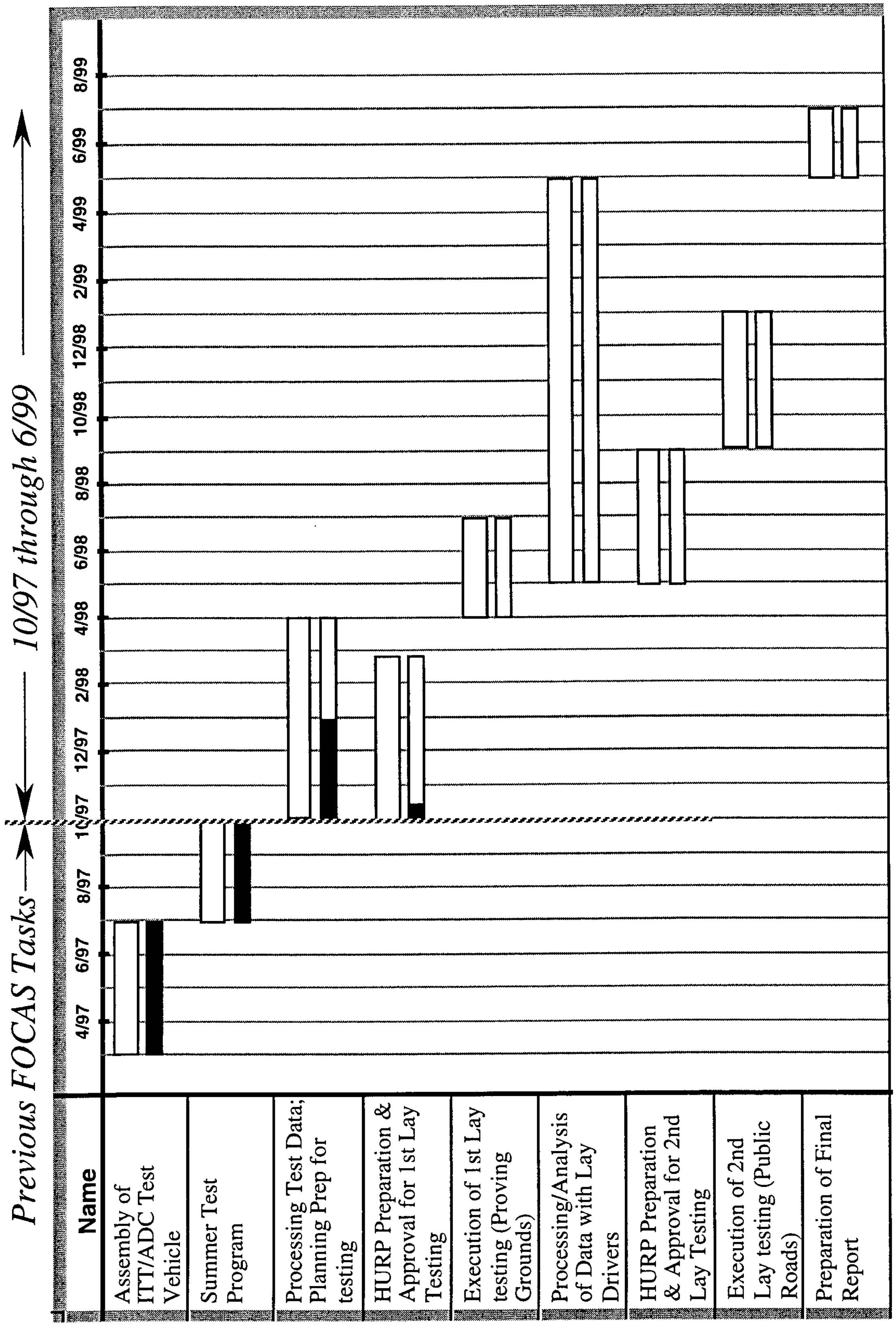

Figure 33. FOCAS Activity schedule

The objective of the first-stage tests, involving cruise control only, will be to see when the driver chooses to intervene in the respective closing and lead-vehicle-braking situations. In order to achieve closing, of course, the set speed of the following vehicle must be made larger than that of the impeding vehicle. As the test proceeds, the range between the vehicles will decrease until the driver decides to intervene by braking. The results from this test will indicate the headway conditions in which the driver feels braking should commence, as well as the braking level which is deemed appropriate for these conditions.

The objective of the companion test involving braking by the preceding vehicle is also to see when the driver chooses to intervene. In this test, both vehicles are initially proceeding at the same speed at a preselected value of headway range. Then the preceding vehicle decelerates in a prescribed manner. As the test proceeds, the range will decrease until the driver of the following vehicle decides to intervene. The level of braking exhibited in the intervention response will be employed as a convenient surrogate for driver anxiety.

Once a given driver's characteristics have been estimated from the results of that person's first-stage tests, a set of braking parameters for the ACC system will be selected to mimic his/her behavior in managing headway. A corresponding reference set of parameter values will have been selected to represent the best of UMTRI's accumulated views on good ACC performance. Each driver in the stage-two testing will experience their own "headway-clone" form of ACC controller as well as the "UMTRI-reference" form of controller. Some of the drivers will operate with the reference controller first and others will use the headway-clone controller first. At this point, it is not clear exactly which of three algorithmic possibilities listed in section 4.2.2 will be used, but it is anticipated that the reference system might be based upon the first possibility and the driver-oriented set might use the third possibility where the anxiety function is represented explicitly. In any event, the ACC car can be programmed to switch readily between possible arrangements for generating deceleration commands in the commander unit of the ACC system. Driver opinions combined with quantitative physical data will be examined to guide the selection of the ACC system parameters to be employed in the highway-testing exercise.

In highway operation, of course, conflict situations are not controlled in the sense of a proving-grounds test. The purpose of highway testing is to see if the system performs its function properly in a real environment and if there are any side effects that cause difficulties in driving situations that occur naturally. Driver opinions and observations are important in determining the meaning of the quantitative physical data gathered during on-road testing. Clearly, the ultimate evaluation of the ACC system with braking and warning will hinge upon experience in a natural driving environment.

5.2 Driver Modeling

We anticipate learning more about the driver's mental model, although, at present, only the most fundamental and simplified abstractions have been applied to aid in understanding the task of controlling the headway to an impeding vehicle. Nevertheless it has been helpful to consider three levels of cognitive processes running from knowledge to rules to skills and associating symbols, signs, and signals with each of these respectively. The use of these ideas in comparing manual driving with ACC driving has become a fundamental means for addressing the goals of the FOCAS project. We anticipate further use of these cognitive concepts in addressing the subject of headway control and forward collision warning. We hope the tests performed and data provided will allow us to better understand what drivers perceive, when they decide to use the brakes, and the headway time gaps they choose to use.

5.3 Minimizing Risk Exposure

We expect that we will advance the understanding of how ACC systems could influence safety by reducing the amount of exposure to the risk associated with traveling at short headway time gaps. Traditional safety work addresses both crashworthiness and crash avoidance where crashworthiness involves the probability of injury given a crash and crash avoidance often involves the probability of a crash given some measure of exposure. The usual approach to crash avoidance seems to entail defining a type of crash and then evaluating the importance of that crash type by estimating the percentage of all crashes represented by that type. The number as well as the severity of the crashes is taken into account in assessing importance. However, when it comes to creating countermeasures, it seems that the emphasis in many crash-avoidance concepts is placed on doing something at the last moment so as to almost miraculously resolve an impossible situation. There is another conceptual way to avoid crashes, and that is to avoid getting into these nearly impossible situations in the first place. An ACC system, for example, has the potential for avoiding crash scenarios that would otherwise have been initiated by following too closely.

Figure 34 has been created to illustrate three directions for improving safety by reducing risk. These directions are associated with injury given a crash, crash avoidance given a problem in a risky situation, and exposure to risky situations. As indicated in the figure, the probability of injury is related to a volume in the injury-crash-exposure (ICE) space—the volume of the ICE cube. Even though manufacturers may portray ACC systems as convenience devices, such systems could have an impact on injury rate by shrinking the exposure dimension of the ICE cube. Furthermore, certain types of forward collision warning systems could be aimed at reducing the exposure to risk associated with closing in on an impeding vehicle too rapidly for the driver's skill and experience to be effective. In the coming year, the FOCAS project is expected to focus on countermeasures aimed at reducing the exposure to risk.

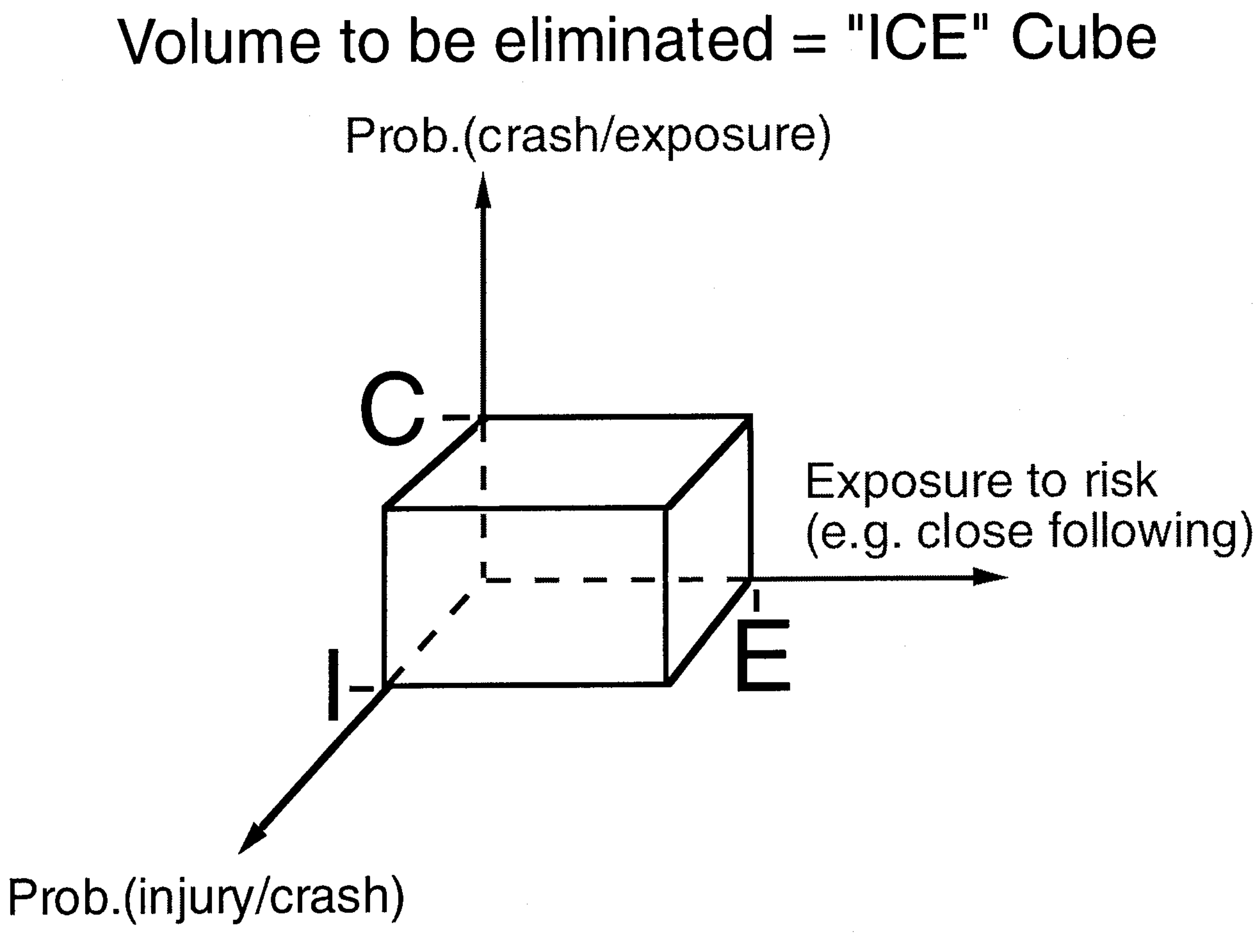

Figure 34. Injury , crash, exposure (ICE) cube

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